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Institute of Oceanography
Old Dominion University
Norfolk, Virginia

Technical Report No. 11

Evaluation of Submarine Strain-Gage Systems for Monitoring Coastal Sediment Migration

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Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Langley Research Center
Hampton, Virginia 23365

Under
Master Contract Agreement No. NAS1-9434
Task Order No. 54

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ABSTRACT

Single and multiple strain-gage systems were respectively evaluated as in situ point and areal sensors for monitoring sand-height variations in coastal environments. Static loading tests indicate that gage response pressure is linear for sand heights up to 24 inches. Response pressures are a function of both sand height and aggregate density, with density being influenced by both sediment texture and degree of compaction. Poorer sediment sorting and greater compaction result in higher response pressures. Dynamic loading tests conducted in a re-circulating flume indicate that gage response is not significantly influenced by either hydraulic flow velocity, or the migration rates of varying-textured bed forms. Response dispersion levels under dynamic conditions are formidably high, as a result of packing and density inconsistencies induced by transport processes. This results in sufficiently low reproducibility to critically limit the systems' potential as quantitative research instruments.

Field tests in a beach foreshore environment indicate that the gage systems are effective qualitative instruments for monitoring long-period migration trends of beach sediments; whereas, short-period responses are not sufficiently reliable. The durability and compactness of the gage systems must be substantially increased for effective field operations. It is recommended that the systems' qualitative potentials be further developed, whereas their development as quantitative instruments be terminated. Further development should emphasize the construction of remote recording systems designed for semi-permanent installation.

ACKNOWLEDGMENTS

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INTRODUCTION

Coastal zones are among the most dynamic of all geologic environments. They are characterized by natural erosional and accretionary processes that result in the nearly constant migration of tractional sediment, the dynamics of which are only vaguely understood. The coastal transport of tractional sediments, which consist largely of sand-size particles, results in many critical coastal zone problems such as 1) beach erosion, 2) the development of coastal shoals that are hazardous to navigation, and 3) the destruction of navigable harbors and inlets by sedimentation.

In planning remedial programs for coastal zone problems, studies by oceanographers and coastal engineers designed to gain insight into the dynamics of coastal sediment migration are mandatory. One of the most basic aspects of such studies involves monitoring the beach and adjacent seafloor at selected sites, in terms of sediment erosion and accretion, as a function of time. Areal studies based on sediment monitoring can provide quantitative and qualitative data regarding the rates and directions of coastal sediment dispersal. In turn, these data can lead to the development of valid conceptual and mathematical models of coastal sediment transport systems, a necessary prerequisite for the establishment of effective remedial measures to combat coastal zone problems.

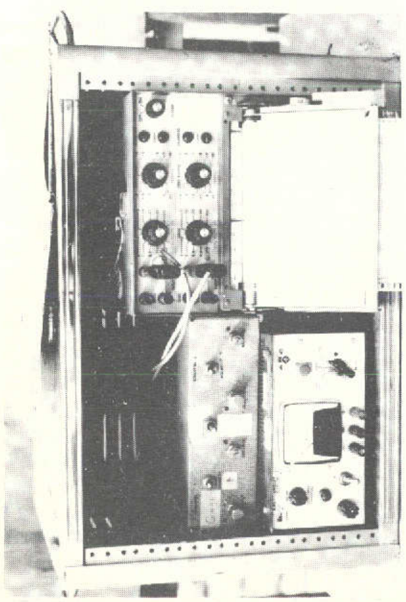
At present, the main techniques of monitoring sediment migration in coastal environments consist of obtaining a time-series of topographic profiles. In submarine environments, this requires costly high-precision shipborne surveys employing sea sleds or echo sounding equipment. These surveying techniques are only capable of detecting relatively large-scale changes. Smaller-scale changes must be observed manually by periodically inspecting graduated metal rods implanted in the beach, or by scuba divers observing rods implanted on the sea floor. These various techniques are not only dependent upon favorable weather conditions, but are also costly and highly inefficient from the standpoint of the required logistics. Researchers concerned with evaluating sedimentary processes in coastal zones have clearly demonstrated a need for instrumentation capable of providing inexpensive in situ measurements of sediment changes at close intervals, over extended periods of time. Data of this nature could not be obtained on a practical basis by any of the existing techniques; however, with present technology, the possibility now exists for developing in situ sensing instrumentation capable of providing such data.

A preliminary study to evaluate the feasibility of employing an in situ sensor for measuring sand-height fluctuations in a coastal marine environment was conducted by Swift and McGrath (1972). They tested an early model sand-height gage that proved to be of very limited utility, but which did illustrate the potential of the strain-gage technique for measuring sand heights. The purpose of the present study is to evaluate the effectiveness of two new and improved strain-gage systems as oceanographic research instruments. One instrument package consists of a single-gage system which is evaluated as a point sensor; whereas, the other package consists of a multiple-gage array system which is evaluated as an areal sensor providing synoptic data. It was believed that an evaluation of these new gage systems might result in the development of practical, low-cost instrumentation for obtaining in situ sand migration data in active coastal areas.

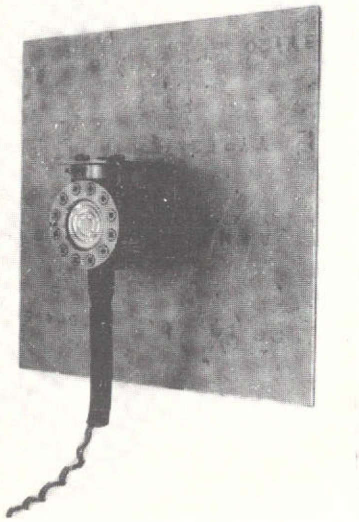
INSTRUMENTATION

The sand gage used in the single-gage system is a Consolidated Electrodynamics Corporation's (CEC) Type 4-351 pressure transducer (Fig. 1B). This gage is a bi-directional differential pressure transducer utilizing the unbonded strain gage principle, with a four-active-arm spring-type sensing element and a force-summing diaphragm. It has a two-inch diaphragm, a pressure range of ±5 psid., and an operable temperature range between -65°F and 275°F. The reference and active sides of the instrument can tolerate corrosive fluids and gases similar to the capability of 300-series stainless steel. The major technological application of this transducer model is measuring differential pressures in fuel and oxidizer lines on missile and booster engines (Bell & Howell Specification Sheet). The gage was mounted on a 1 sq. ft. stainless steel plate for stability in the field. The remainder of the instrumentation included a Honeywell Electronic 19 (2 channel) strip-chart pen recorder, a regulated power supply, and a balance and sensitivity control unit (Fig. 1A). During the field testing, electrical power was supplied by a gas-driven Sears 3000 Alternator.

Figure 1. Instrument packages for the single-gage system (A, B), and the multiple-gage array system (C, D).



A



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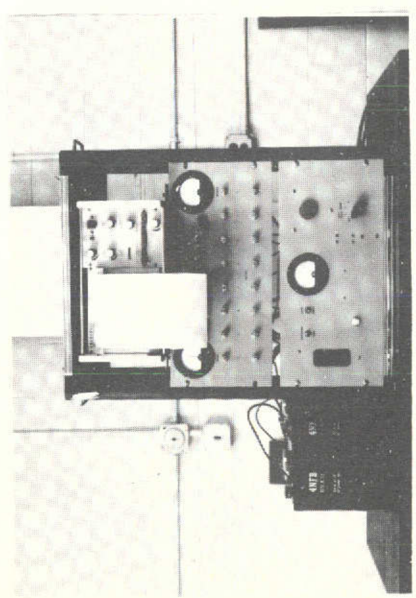
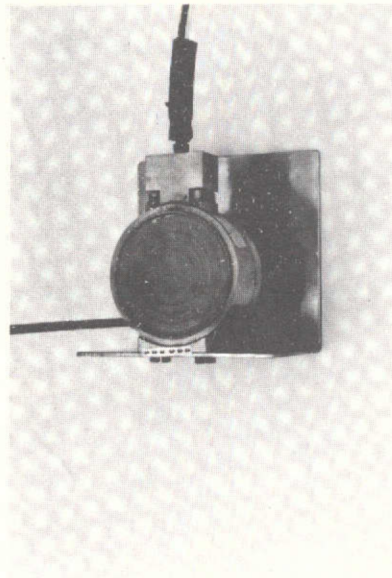


C



D

The six gages used in the multiple-gage array system are modified Bell & Howell Type 4-451-0100 pressure transducers (Fig. 1D). This bi-directional differential transducer is a bonded strain-gage instrument with a 4-inch diaphragm, and a pressure range of ± 5 psid. The recorder for this system is a model 2206 Honeywell Oscillograph (Fig. 1C). This 12-channel recorder is mounted in a steel cabinet together with a balance and sensitivity control module. Electrical power is supplied by two heavy duty 12-volt batteries. The differential pressure transducers utilized in this study essentially nullified any pressure variations resulting from the hydraulic column itself, thereby sensing only sand pressures.

METHODS

This study was conducted in three separate phases consisting of static loading tests, dynamic loading tests, and field tests. The static test series was performed on the single-gage system to evaluate the influences of sediment texture and compaction on gage response characteristics; this was performed to ascertain the feasibility of utilizing the strain-gage technique in measuring sand heights. Dynamic tests were conducted on both single-gage and multiple-gage systems to evaluate their responses under controlled conditions that simulate a natural hydraulic system. Field tests were then conducted on both gage systems to evaluate their durability and performance under actual field conditions.

Test Sand Description

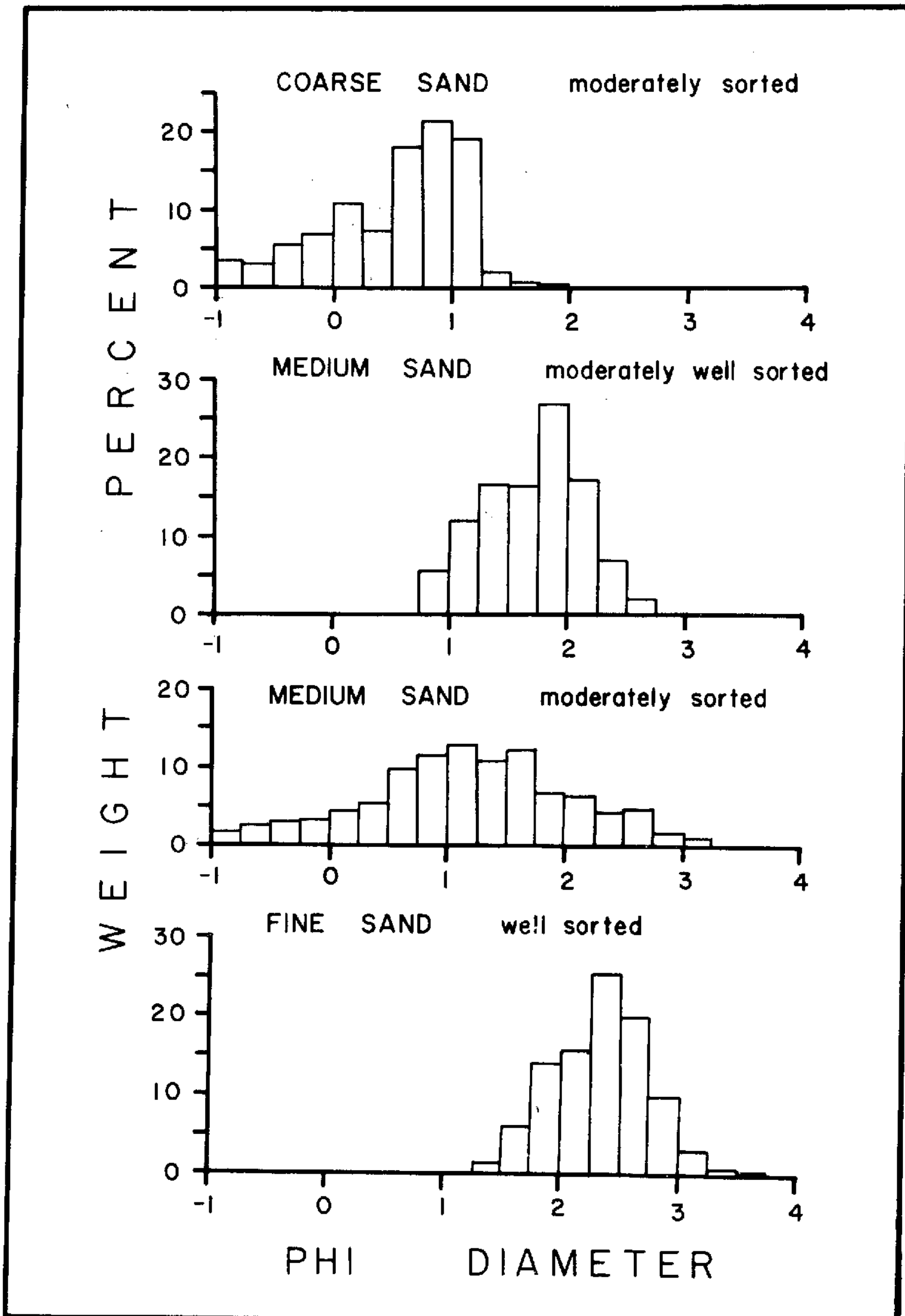
In order to evaluate the influence of sediment texture on gage response, a series of four tailor-made test sands with specific textural characteristics were manufactured in the laboratory. This was accomplished by hand-sieving voluminous quantities of stock sand to achieve the desired specifications. The stock sand is quartoze, and was derived locally within the Tidewater area.

Descriptive parameters of the four test sands are presented in Table 1, and their size frequency distributions are illustrated by histograms (Fig. 2). Employing the terminology of Folk (1968), the test sands are: 1) a well-sorted fine sand, 2) a moderately-sorted medium sand, 3) a moderately well-sorted medium sand, and 4) a moderately-sorted coarse sand. In achieving a representative size analysis of such a large quantity of sand, five sub-samples were combined, then split into a 50-gram composite sample and sieved at a 0.25 Ø interval on a RO-TAP for 15 minutes. Histograms were plotted, and Folk's (1968) statistical parameters were tabulated from cumulative curves plotted on log-probability paper.

Table 1. Descriptive parameters of test sands.
(terminology from Folk, 1968).

Sand Type	Mean Grain Size	Modal Diameter	Sorting	Porosity
Coarse Sand Moderately-sorted	0.50 Ø	0.75 - 1.00 Ø (0.50 - 0.59 mm)	0.72 Ø	26.5%
Medium Sand Moderately-sorted	1.17 Ø	1.00 - 1.25 Ø (0.42 - 0.50 mm)	0.89 Ø	25.3%
Medium Sand Moderately well-sorted	1.72 Ø	1.75 - 2.00 Ø (0.25 - 0.30 mm)	0.56 Ø	28.6%
Fine Sand Well-sorted	2.30 Ø	2.25 - 2.50 Ø (0.177 - 0.210 mm)	0.49 Ø	28.1%

Figure 2. Histograms illustrating the size frequency distributions of the four test sands. PHI diameter is the negative log of the grain diameter in millimeters, to the base 2.


COARSE SAND moderately sorted
MEDIUM SAND moderately well sorted
MEDIUM SAND moderately sorted
FINE SAND well sorted
PERCENT
WEIGHT
PHI DIAMETER
0
10
20
30
-1
0
1
2
3
4

The porosity for each test sand was empirically determined in the laboratory by pouring 2000 ml of each sand into a large glass jar. The sides were gently tapped and the compacted level was marked on the jar. Water was then added in measured increments until it completely saturated the sand. Occasionally, it was necessary to disturb the original packing configuration to insure total saturation. The side of the jar was again tapped with a rubber mallet until the original sand level was re-established. Excess water was pipetted off, and the final volume of pore water calculated; test sand porosity values are presented in Table 1.

Static Loading Tests

Static loading tests were conducted in a 3/4"-thick fiberglassed, marine plywood box measuring 3'x3'x4'. The transducer was initially placed at the bottom of the box, and packed with sand until the diaphragm was flush with the sand; water was then added to a height of 24 inches above the sand gage. Sand was gradually introduced into the water column, and allowed to gently settle over the gage. At increments of 2-3 inches, the sides of the box were agitated by striking with a hammer, in an attempt to induce a more stable packing arrangement. The sand height was then measured, recorded, and the process repeated until a sand height of approximately 24 inches was achieved. Once the test was started, it was necessary to continue uninterrupted because of increased compaction effects that would occur if left unattended for extended periods of time. This entire procedure was repeated three times for reproducibility with each of the test sands, and resulted in a moderate degree of compaction. In order to evaluate sediment compaction on gage response, static tests were also conducted under "unagitated" and "superagitated" conditions. In the unagitated test, extreme caution was practiced to gently load the sand to a height of 24 inches without vibrating the box; this was done to minimize settling, and simulate a relatively uncompacted sediment. The superagitated test was conducted by thoroughly agitating the sand at 10-12 equally spaced points with an electric vibration rod during loading. Each vibration lasted 1-2 minutes, and a relatively high compaction state was simulated.

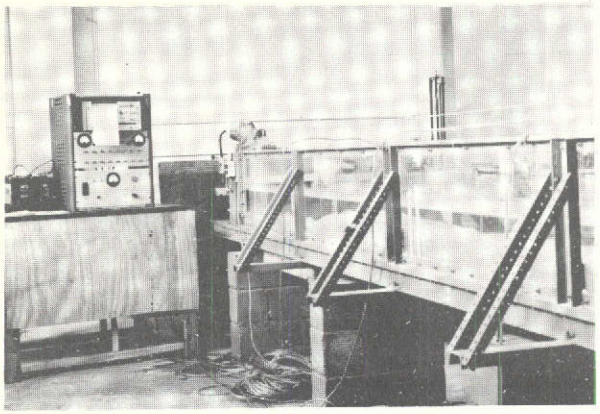
Dynamic Loading Tests

Dynamic loading tests were conducted in a re-circulating hydraulic flume located in the Hydraulics Laboratory at the Institute of Oceanography, which permitted a variable flow velocity (Fig. 3A, 3B). The overall length of the flume is 24 feet, with the observation section measuring 16 ft. in length, 18 in. in width, and 10 in. in depth. Water flow is directed by the lower unit of a Johnson 18 HP outboard motor which is pulley-driven by a variable speed 1.5 HP electric motor. Three recessed-troughs were built into the bed of the flume to accomodate up to six sand gages. The flume geometry permitted a maximum sand load of 6 inches.

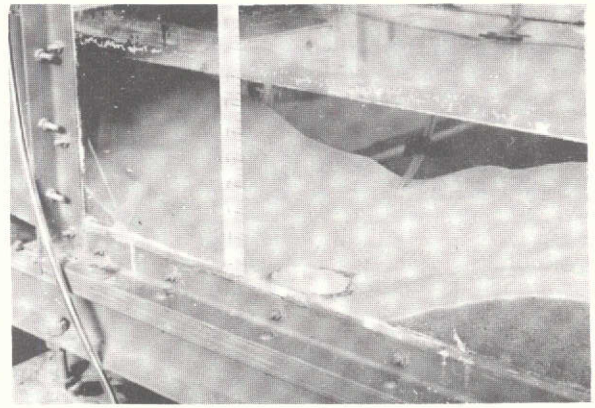
During dynamic testing, the gages were implanted with the diaphragm flush with the flume bed (Fig. 3B). All sand was removed from the immediate vicinity to artificially form a sand dune upstream from the gage. These sand dunes measured 6 in. in height, and dipped towards the sand gages at angles approaching the maximum angle of repose. Prior to the initiation of the test, water temperature, water depth, and height of the sand bed were measured. Flow velocities for each of the tests varied according to the water height, thickness of the sand bed, and bed form morphology. The relatively low velocity runs for each test sand were conducted at the lowest velocity that initiated grain movement and the formation of sand ripples; the high velocity runs were conducted at the maximum flow velocity that was attainable under the given conditions in the flume, while the medium velocity tests were conducted at a velocity approximately half way between the high and low velocity runs. One recurring problem throughout the dynamic testing was poor visibility. Visibility was particularly limited when using the fine sand. To help alleviate this problem during the fine and medium sand tests, the flume was constantly being flushed with fresh water to remove suspended sediment.

After each gage achieved maximum deposition, the sand was removed from each gage at one-inch increments, by artificially inducing scour. This unloading procedure was conducted to determine if erosional and accretionary processes induced different gage response characteristics. Each dynamic test was run three times for reproducibility at a relatively low, medium, and high velocity. The absolute velocities varied within, and between each test, depending upon bed form configurations. Competent flow velocities attainable

Figure 3. Illustration of dynamic testing in re-circulating flume (A, B), and field testing operations (C,D).

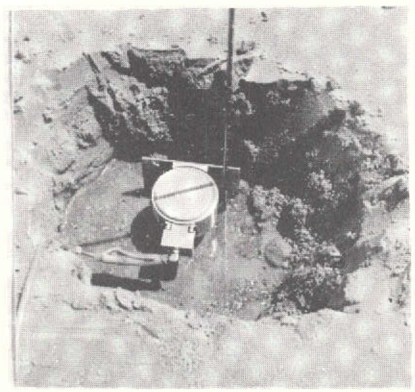


A



B

C



D

in the flume ranged between 1.0-2.2 ft/sec. Generally, the low velocity tests averaged 1.3 ft/sec, and the medium velocity tests averaged 1.6 ft/sec; the high velocity tests averaged 2.0 ft/sec.

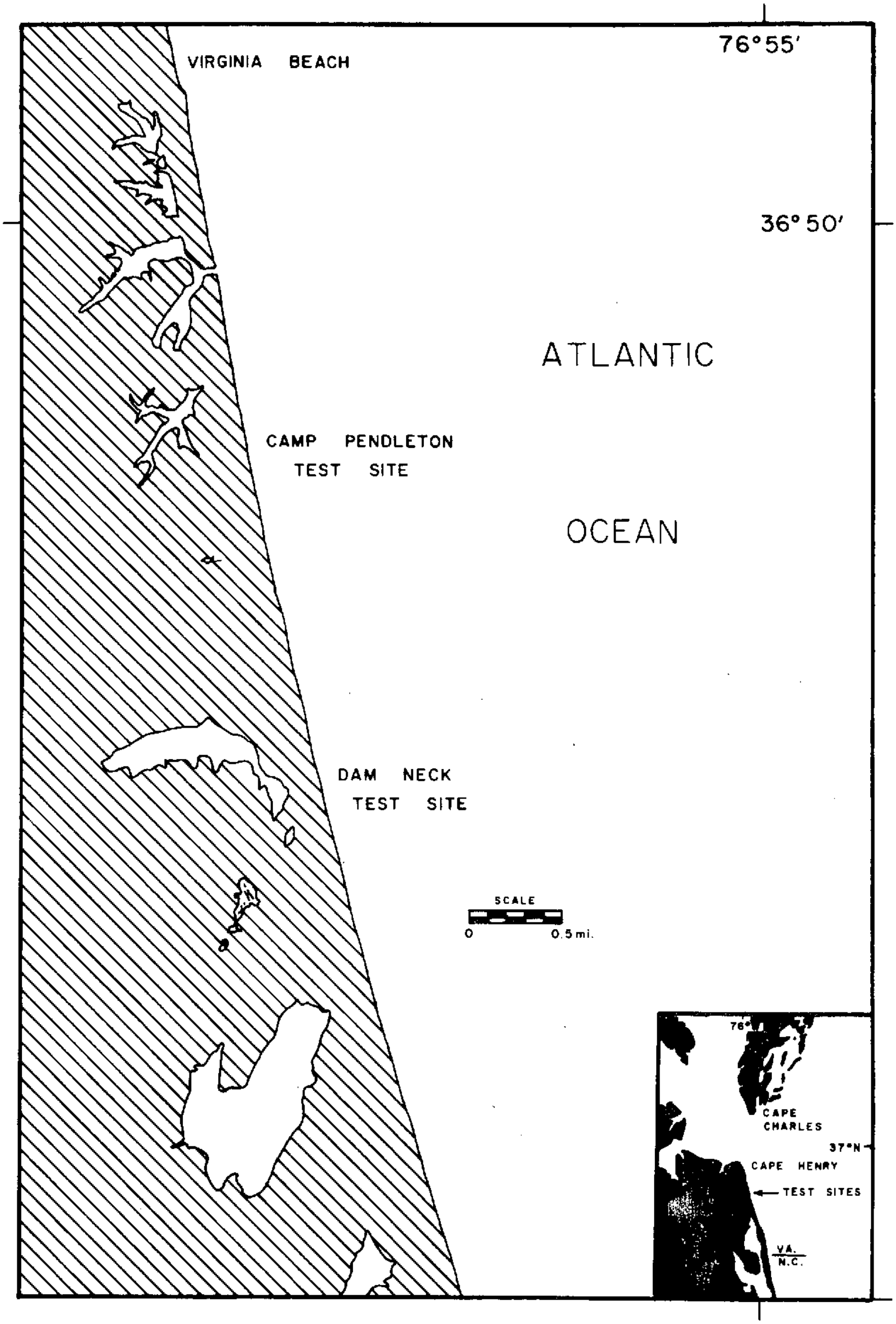
Flow velocities were measured by two methods. Average surface velocities were measured by timing a neutrally buoyant plastic float over a measured 10-foot distance. This was done five times for reproducibility, and repeated several times during each test. All values were then averaged to determine a final mean velocity for each test. The second method of velocity measurement utilized a drag sphere strain-gage current meter. The force exerted on the drag sphere is the resultant hydrodynamic drag across the entire projected area of the sphere (Blair, 1973); this current meter provided an average velocity value over a relatively small area.

Field Testing

Both the single-gage and multiple-gage array systems were field tested to evaluate their performance under natural conditions, in terms of both their response characteristics and durability. Field tests were conducted within the beach foreshore environment at two test sites along the open coast of southeastern Virginia (Fig. 4). Each field test commenced at low tide, and efforts were made to extend the test period over one complete 12-hour tidal cycle, in order to detect sedimentation effects during both the transgressive flood tide and the subsequent regressive ebb tide. However, some tests terminated prematurely because of equipment failure.

The inter-tidal beach foreshore environment was selected as a test site because of its relatively high rate of sediment migration. Foreshore sedimentation is complex, and has been studied in detail by several investigators (e.g. Inman and Filloux, 1960; Duncan, 1964; Otvos, 1965; Strahler, 1966; Schwartz, 1967). In general, it can be characterized as consisting of cyclic patterns of erosion and accretion induced by the semidiurnal tidal cycle These patterns migrate at a relatively rapid rate, thus offering optimum conditions for evaluating gage pressure-sand height responses. In addition, a rising tidal level along a foreshore would sequentially subject the gages to a variety of high energy hydraulic flow systems occurring in the swash-backwash zone, surf zone, and breaker zone. These conditions appeared to be optimally suited for effective field testing.

Figure 4. Location map showing the two field test sites.



76°55'
VIRGINIA BEACH
36°50'
ATLANTIC
OCEAN
CAMP PENDLETON
TEST SITE
DAM NECK
TEST SITE
SCALE
0
0.5 mi.
76°
CAPE
CHARLES
37°N
CAPE HENRY
TEST SITES
VA.
N.C.

11-A

To measure both erosion and accretion on the beach foreshore, it was necessary to initially bury the sand gages (Fig. 3D). The gages were buried just above the swash mark at low tide to allow maximum transgression during the rising tide. It was not feasible to keep the burial depth constant, but a minimum burial depth of 4 inches was maintained; the gages were normally implanted either at the water table, or slightly below it. In testing the multiple-gage system, the array gages were deployed in two rows, each containing up to three gages. Each sand gage was spaced 10 feet apart, with the second row of gages being five feet shoreward of the first row, but implanted midway between the gages of the first row (Fig. 3C); occasionally, some gages of the shoreward row were implanted above the water table level. It was believed that this spatial arrangement would be best suited for detecting sediment migration patterns over the foreshore. Also, the spacing within each row was close enough to serve as a check on the adjacent gage reading in the event of individual gage failure.

All gages were affixed with a measuring rod, graduated in one-inch increments above the diaphragm. After a sand gage was buried, its respective recorder channel was balanced to an arbitrary zero reference pressure. This was done because of the limited excursion allowed for each trace line on the recorder. It was from this reference point that all increasing pressures (accretion) and all decreasing pressures (erosion) were measured. Consequently, all recorded pressure values have relative, rather than absolute significance. The single-gage system was operated on a continuous basis; whereas, the multiple-gage system was only activated for a 5-minute period each half-hour because of its relatively high power requirements. At half-hour intervals, the height of sand over the gages was visually measured from the graduated rods, and recorded in a field notebook and on the chart paper. Positions of the gages with respect to the swash-backwash zone, the surf zone, and the breaker zone were also noted. Full duration tests were terminated at the following low tide when the swash mark fell below the gage positions. During the field tests, supplemental data were also acquired regarding meteorological, sea state, and beach conditions. A tent was erected on the beach to protect the equipment and provide shelter for the field crew.

Gage Calibration and Record Interpretation

Calibration of the single-gage system was accomplished by using a special adaptor plate that fitted over the gage diaphragm. The diaphragm was pressurized using a manometer and bellows at increments of 0.2 psi, to a maximum pressure of 1.2 psi. The linear calibration record was recorded on the strip chart, and repeated several times during the series of static, dynamic, and field tests. A CAL signal was also built into the system to provide a quick check of the gage's sensitivity. After a warm-up period of 10-15 minutes, the CAL signal which corresponded to a known pressure value was activated. This was done before any sand was loaded onto the gage, and after all sand was removed, in order to insure that no sensitivity changes had occurred. The chart paper for this system's recorder was 6 inches in width, and graduated into 100 evenly-spaced divisions. Due to the thickness of the ink pen, interpretation was carried out to the nearest 0.5 division. The corresponding pressure values were then calculated using a simple ratio test based on the value of the CAL signal.

Calibration of the array gages used in the multiple-gage system followed an identical procedure, except that a vacuum was pulled on the reference side. This system also had a built-in CAL signal which was used before and after each test. The grid on the oscillograph chart paper was wider than on the chart paper of the single-gage system, and the interpretation was carried out to the nearest 0.3, 0.5, 0.7 or whole number. The chart paper was the same width (6 inches), but the sensitivity was reduced and the total excursion allowed for each trace was less.

DISCUSSION OF RESULTS

Static Loading Tests

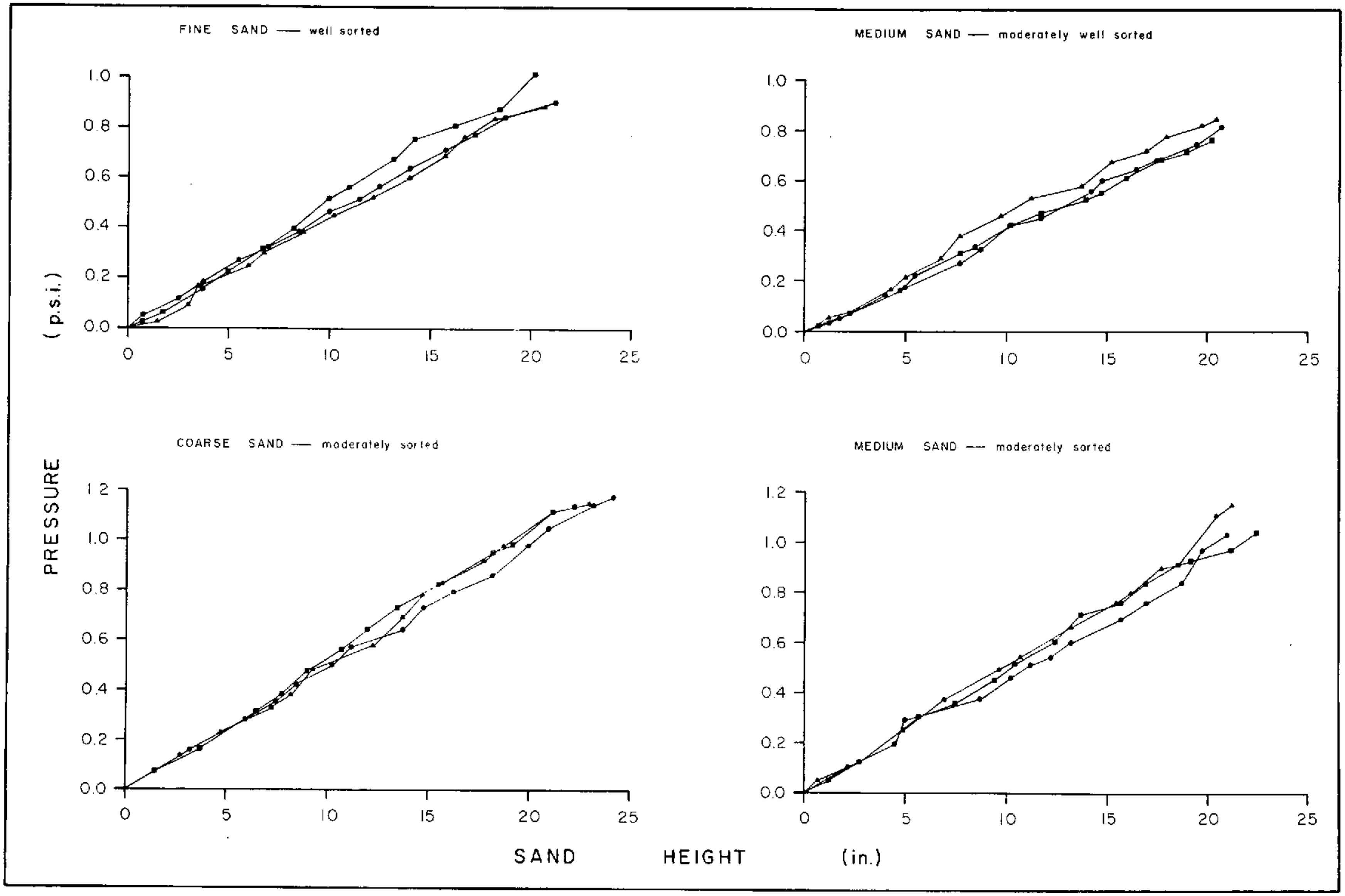
In an effort to evaluate the influences of both sediment texture and sediment compaction on gage response characteristics, static tests were conducted with the single-gage system to minimize extraneous variables, and approach optimum conditions of controlled experimentation.

Textural Effects

In assessing the influence of sediment texture on gage response characteristics, agitated static loading tests were conducted employing the four test sands described earlier. Maximum sand heights achieved varied from 20.25 to 24.00 inches, with the results illustrated in Figure 5. All tests illustrate linear response pressure (p.s.i.) as a function of sand height, within the load limits tested (< 24 in.). Employing a curve fitting program with a MONROE calculator, linear regression analyses were performed for the four static tests, using the method of least squares. All analysis resulted in correlation coefficients exceeding 0.99, illustrating excellent pressure-sand height relationships; derived linear equation coefficients and correlation coefficients are presented in Table 2. The three replicate trials conducted for each test sand illustrate varying degrees of response dispersion, which can be attributed largely to the combined effects of (1) accuracy variations in sand-height measurements, and (2) real differences in sediment density resulting from inconsistent packing arrangements.

Gage response is not only a function of sediment height, but also sediment density. In a relatively pure quartoze sand, the most influential factor determining absolute density is sediment porosity, defined as the percentage of interstitial pore space volume relative to total sediment volume. In turn, absolute porosity is influenced by a variety of factors which include sediment texture (uniformity, shape) and packing characteristics. Packing refers to the relative spatial arrangement of individual grains in a granular mass (Pettijohn, 1957). Graton and Frazer (1935) have defined a sequence of six systematic packing arrangements, and several haphazard configurations for uniformly-sized spherical grains. The "loosest" type of packing (cubic packing) has the greatest amount of pore space. In cubic packing, the centers of the spheres form the eight corners of a cube. In contrast, the most stable and compact configuration is rhombohedral packing, in which the centers of the spheres form the eight corners of a regular rhombohedron. Porosity values for cubic and rhombohedral packing are 47.6% and 26.0%, respectively. Porosity values of natural sediments are generally intermediate between these two extreme conditions. Packing is more complex in nature because the grains

Figure 5. Results of the single-gage static loading tests using the four test sands. Each sand was loaded under agitated conditions to simulate moderate compaction. Each test consisted of three replicate trials to evaluate dispersion.


FINE SAND — well sorted
MEDIUM SAND — moderately well sorted
COARSE SAND — moderately sorted
MEDIUM SAND — moderately sorted
PRESSURE
(p.s.i.)
SAND HEIGHT (in.)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
5
10
15
20
25

15-A

Table 2. Linear Least Squares Regression Analyses Applied to Static Loading Tests.

Static Test	Slope	Y-Intercept	Correlation Coefficient
Coarse Sand Moderately-sorted	0.64	-0.010	0.996
Medium Sand Moderately-sorted	0.65	-0.003	0.992
Medium Sand Moderately well-sorted	0.50	-0.004	0.991
Fine Sand Well-sorted	0.55	0.000	0.997
Densification Test Well-sorted fine sand	0.89	0.070	0.994
Unagitated Test Moderately-sorted medium sand	0.34	0.12	0.935

are not of uniform size and shape. Generally, the looser packing arrangements occur during initial sedimentation, when the forces of gravity acting upon the grain exceed the effects of fluid flow over the bed (Shepard, 1963). However, during continued settling and compaction, the sediment progressively approached the more stable rhombohedral configuration, resulting in progressively lower porosity and increasing density.

The varying degrees of response dispersion exhibited by the four test sands (Fig. 5) suggests that texturally-influenced density variations resulting from packing and porosity inconsistencies are the dominant causative factor. The best reproducibility was obtained with the moderately-sorted coarse sand (± 8%), whereas the poorest was obtained with the moderately-sorted medium sand (± 16%); intermediate results were obtained with the moderately well-sorted medium sand (± 12%), and the well-sorted fine sand (± 15%). All reproducibility percentages presented in this paper were obtained by expressing the maximum dispersion/total deflection range ratios as percentage values. The lowest amount of dispersion exhibited by the coarse sand might be partially attributed to the higher degrees of grain sphericity and roundness frequently associated with coarse sands, possibly resulting in more consistent packing arrangements. Grain uniformity (sorting) also appears to be an influential factor, as suggested by the 4% reproducibility differential between the two medium sands where sorting is the only variable; this suggests that better sorted sands produce more consistent results.

The influence of sediment texture on gage response is indicated by comparing the absolute pressure differentials among the four sands, as delineated by the slopes of the least square regression lines (Table 2). A comparison of the two medium-grained sands illustrates that the more poorly sorted of the two produces higher pressures over the entire response range, illustrating that sorting is an important influential factor. Increased pressures resulting from a decrease in sorting can be attributed to a reduction in porosity resulting from the smaller-size grains settling and filling interstices between the larger grains. This is supported by laboratory measurements of test sand porosity, which illustrate a 3.3 percent differential between the two medium sands (Table 1); the poorer-sorted sand exhibits a porosity of 25.3%, as compared to 28.6% for the better-sorted sand.

In contrast to sorting, the influence of grain size appears to be of relatively minor significance, as suggested by the very similar response of the moderately-sorted coarse sand (26.5% porosity) and the moderately sorted medium sand (25.3% porosity); in this comparison, the only major variable is grain size, resulting in a porosity differential of only 1.2 percent, and a regression line slope differential of only 0.01. The only test comparison which suggests that grain size may be somewhat influential on gage response is the slightly higher pressures of the well-sorted fine sand, as compared to the moderately well-sorted medium sand (.05 slope differential). This sorting-pressure relationship is at variance with the other test sand comparisons, suggesting that finer sands may produce higher pressures irrespective of sorting characteristics. As noted by Pettijohn (1957, p. 86), grain size should be theoretically non-influential in determining sediment porosity, although it has been empirically established that finer-grained natural sediments generally have higher porosity than the coarser-grained sediments; this may result from associated differences in grain shape. However, laboratory measurements of porosity for the two test sands illustrate no significant porosity differential (e.g. 0.5%). Consequently, the higher pressures exhibited by the fine sand, relative to the medium sand, may result from the influence of grain size on some sediment parameter other than porosity, If grain size is influential on gage response, as suggested by this test comparison, it is highly subordinate to the influence of sorting.

Compaction Effects

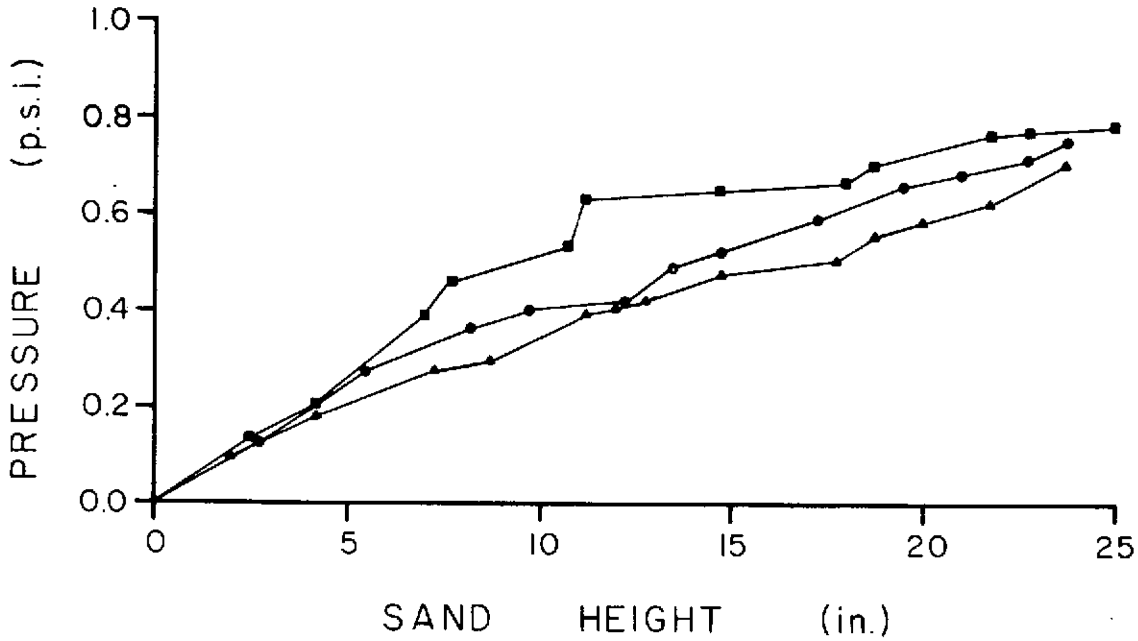
In an effort to evaluate the influence of sediment compaction on gage response characteristics, selected test sands were loaded under varying agitation and settling conditions. Compaction resulting from natural settling and the application of external lithostatic pressures results in the spatial orientation of individual grains comprising the sediment aggregate. Continued compaction tends to produce progressively tighter packing arrangements, with a concomitant reduction in porosity and expulsion of interstitial pore fluids. Therefore, the increasing aggregate density should produce progressively higher gage response pressures, as a direct function of compaction state. As noted by Jumikis (1962), compaction may affect a soil by (1) increasing its density, shear strength, and bearing capacity, (2) reducing the tendency for the soil to settle under repeated loads, and (3) decreasing the permeability. Interstitial fluids may also affect sediment properties. Slight temperature changes may affect fluid viscosity, surface tension,and density, thus also influencing the density of a sediment aggregate.

The influence of compaction on gage response was evaluated by comparing test sands statically loaded under unagitated (relatively uncompacted), agitated (moderately compacted), and superagitated (highly compacted) conditions. The moderately-sorted medium sand was loaded in a totally unagitated state to simulate an uncompacted sediment (Fig. 6), and compared with the same sand loaded under agitated and moderately compacted conditions (Fig. 5). The unagitated response curves exhibit relatively poor full range linearity compared to the agitated curves. The unagitated curves are linear to a sand load of approximately 7 inches, beyond which they exhibit curvilinear response tendencies; poorer linearity of the unagitated curves is quantitatively indicated by a .06 reduction in correlation coefficient. A similar nonlinear response for unagitated fine sand was noted by Swift and McGrath (1972) in the testing of a previous sand gage. They attributed this response to a "bridging effect" resulting from the semi-solid behavior of sediment above a critical loading height, whereby lithostatic pressure is transmitted laterally, rather than vertically. If this "bridging effect" is a real influence in the present test sand, it appears to be significantly reduced through agitation and compaction. The reproducibility of the unagitated curves is poor (± 32%), as compared to the agitated curves (± 16%). The doubled amount of relative dispersion in the unagitated state can be attributed to much greater variability in fortuitous packing arrangements; whereas, the agitated state tended to produce more consistent and systematic packing. The effect of compaction on gage response is well illustrated by the pressure differentials exhibited by the curve envelopes for the two sands. The envelopes are similar within their mutual linear range up to a 7-inch load, beyond which the pressure differential becomes progressively greater with increasing sand height. Using envelope midpoints at a 20-inch sand height for reference, the agitated sand exhibits 0.33 p.s.i. more pressure than unagitated sand. Substantially higher pressure for the agitated sand is also illustrated by a much higher regression line slope coefficient for the agitated sand (0.65), compared to its unagitated counterpart (0.34). This can be attributed to the relatively lower porosity of the agitated and moderately compacted sand, as a result of a closer approach toward rhombohedral packing.

Figure 6. Unagitated single-gage static test using the moderately-sorted medium sand, simulating relatively uncompacted loading conditions. Three replicate trials conducted for evaluating dispersion.

UNAGITATED STATIC LOADING TEST

MEDIUM SAND —— moderately sorted



A further evaluation of compaction effects was conducted by means of a densification test, whereby the gage response of a "superagitated" well-sorted fine-grained sand (Fig. 7) was compared with its agitated counterpart (Fig. 5); these two test sands represent simulated highly compacted and moderately compacted sediments, respectively. The response curve of the highly compacted or densified sand illustrates good linearity over the entire response range ($r = 0.994$). At sand heights greater than 5 inches, the superagitated sand exhibits substantially higher pressures than the agitated sand, with a pressure differential of 0.40 p.s.i. at a 20-inch sand height. Presumably, the pressure differential could be further increased by prolonged densification. Substantially higher pressures for the superagitated fine sand are also reflected by the much higher regression line slope coefficient (0.89), compared to the agitated fine sand (0.55). The higher pressures exhibited by the superagitated sand, relative to both agitated and unagitated test sand, reflect the highest degree of compaction and tightest packing arrangement obtained during this study. These comparisons of the three agitation states illustrate a progressive increase in gage pressure with increased compaction. Since compaction and packing are highly variable in natural occurring sediments, this series of tests illustrates a major quantitative limitation of the evaluated gage system. The limitation consists of the gage's inability to distinguish between pressure variability resulting from sand height fluctuations, and that resulting from aggregate density variations induced by natural settling and compaction processes.

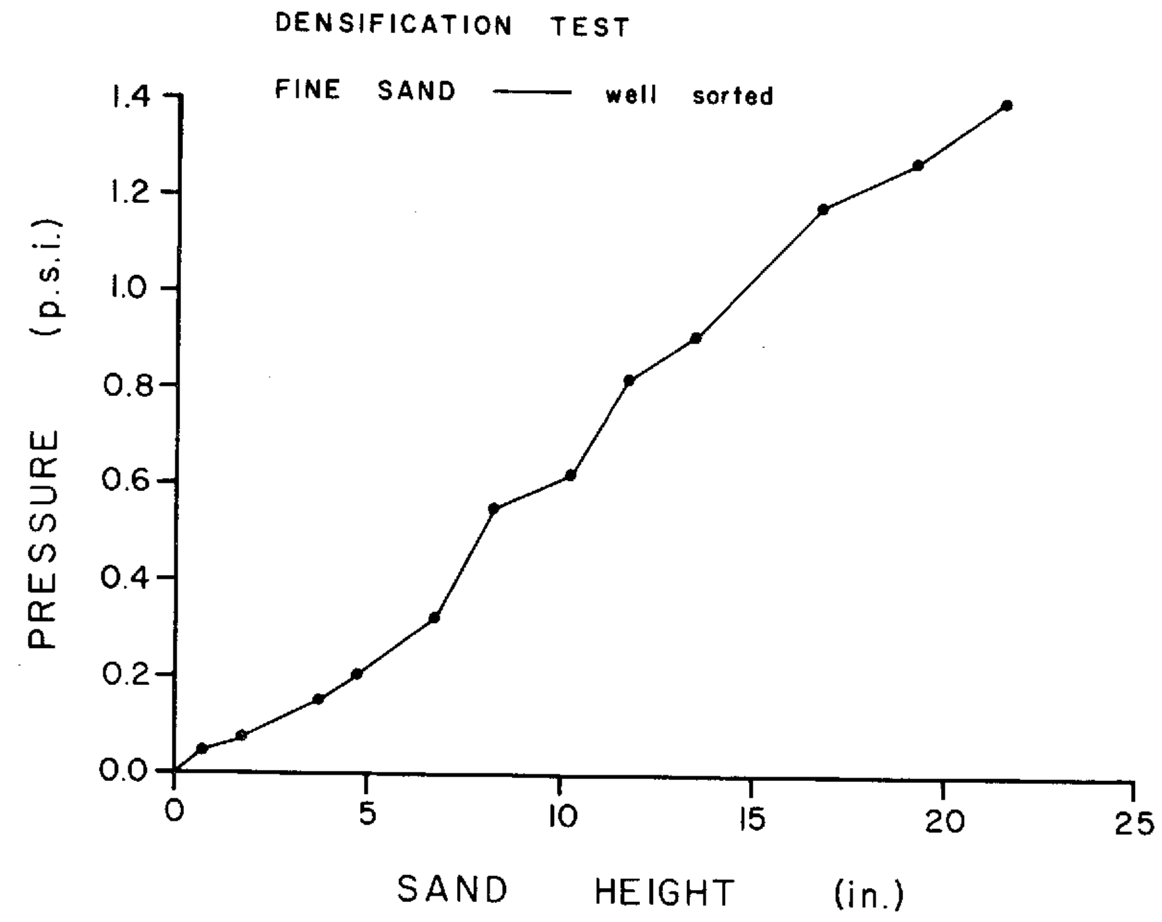
Dynamic Loading Tests

The dynamic loading tests were conducted in a re-circulating flume, using both the single-gage and multiple-gage systems. The tests were designed to evaluate gage performance under controlled dynamic conditions which simulate a natural hydraulic system. In all dynamic tests, a maximum sand load limit of six inches was imposed by the geometry of the flume, and the three test sands used during the dynamic testing were: fine sand-well sorted, medium sand-moderately well sorted, and the coarse sand-moderately sorted.

General

The movement of sand by a fluid is initiated when a critical value of "threshold drag velocity" (Inman, 1963) is exceeded for a particular grain size.

Figure 7. Densified single-gage static test using the well-sorted fine sand. The sand was loaded under superagitated conditions to simulate high compaction.



DENSIFICATION TEST
FINE SAND —— well sorted
PRESSURE (p.s.i.)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
SAND HEIGHT (in.)

22-A

Once movement has been initiated, the sediment layer is deformed and organized into distinct migrating bed forms which constitute the main mechanism of bed-load transport in nature. Employing the bed form nomenclature of Simons and others (1965), the flume-generated bed forms of the present study consisted entirely of ripples (< 0.2 ft. in height) and larger dunes (> 0.2 ft. in height), both of which are representative of the lower flow regime. In migrating asymmetrical ripples and dunes, sand is transported in discrete intermittent steps by migrating up the stoss or upstream face, and avalanching down the steeper lee or downstream face at a slope near the angle of repose. As noted by Brush (1965), a complex of operative sorting processes are associated with this transport mechanism, resulting in the individual bed forms being characterized by internal sorting and grain-size variability. Consequently, internal variations in packing and porosity might be anticipated within an individual ripple or dune. Once generated, bed forms represent obstacles which offer resistance to fluid flow. At ripple or dune crests, flow separates from the boundary layer and develops a reverse-flow stable eddy in the lee of the bed form. Within the eddy zone, deposition appears to occur largely through the collective settling of sediment from suspension (Joplin, 1965; Allen, 1965, 1968); this is then followed by avalanche deposition of foreset beds along the lee slope of the encroaching bed form. These two distinct modes of deposition associated with migrating bed forms might result in packing and sediment density variations during transport, thus influencing gage response characteristics.

In the dynamic flume tests conducted during this study, each gage was positioned so that the initial sedimentation phase occurred within the lee-slope eddy zone created by the construction of an artificial dune upcurrent; this phase was followed by foreset avalanche deposition of the dune itself as downstream migration continued. As a result of the sloping morphology of migrating bed forms, the sand-height measurements obtained represent average heights. It should also be noted that loads from sloping bed forms result in a somewhat unequal pressure distribution over the gage diaphragm. Since factory calibration curves for gages are based upon a uniform pressure distribution, this variance may be a possible source of some error in correlating sand heights with absolute pressure values. The condition that must exist to achieve a uniform pressure distribution is to have the sand level remain constant for a linear distance equal to two times the sand height on either side of the gage (Cheng, personal communication).

Single Gage System

The objective of dynamic loading tests conducted on the single-gage system was to evaluate gage response characteristics for sand migrating as natural bed forms composed of different textures, and at different migration rates. The test results are presented in Figures 8-10.

Coarse-grained bed forms. The results of dynamic testing at three different flow velocities for bed forms composed of the moderately-sorted coarse test sand are illustrated in Figure 8. All three velocity tests result in a basically linear pressure-sand height gage response, although both the low and medium velocity responses do exhibit curvilinear tendencies, as suggested by slight changes in slope above 3-inch load. The three replicate trials for each velocity test illustrate widely varying degrees of response dispersion, which is jointly attributed to both variability in measurement accuracy, as well as sediment density variability resulting from inconsistent packing. Packing inconsistencies can be attributed to both the sorting variability exhibited by migrating bed forms, as well as differential settling and compaction during transport. The latter influence has been observed during extended flume runs when sand height measurements were continuously recorded over substantial time intervals. The measurements indicated substantial increases in pressure for the same sand height, presumably the result of progressive settling with time. The best reproducibility was obtained during the medium velocity tests (± 7%), whereas the poorest was obtained during the high velocity test (± 22%); the low velocity test resulted in relatively good reproducibility of an intermediate degree (± 10%). The relatively higher dispersion of the high velocity test might be partially attributed to higher turbulence, and the greater destructive influence of stronger lee-slope eddys on bed form laminae, possibly resulting in a generally higher degree of packing inconsistency.

The influence of velocity on gage response is illustrated by comparing the absolute pressure differentials on the three velocity tests. The high velocity test exhibits slightly higher pressures than the medium and low velocity tests for a sand load of less than 3 inches, but no significant difference at higher loads. This might be partially attributed to the relatively greater turbulence of the higher velocity lee-slope eddy, and a correspondingly looser packing in the initial sediment laminae resulting from suspension settling. No response difference occurs between the medium and low velocity runs.

Figure 8. Single-gage dynamic loading test of bed forms composed of the moderately-sorted coarse sand, conducted at three different flow velocities. Three replicate trials of each test conducted for dispersion evaluation.

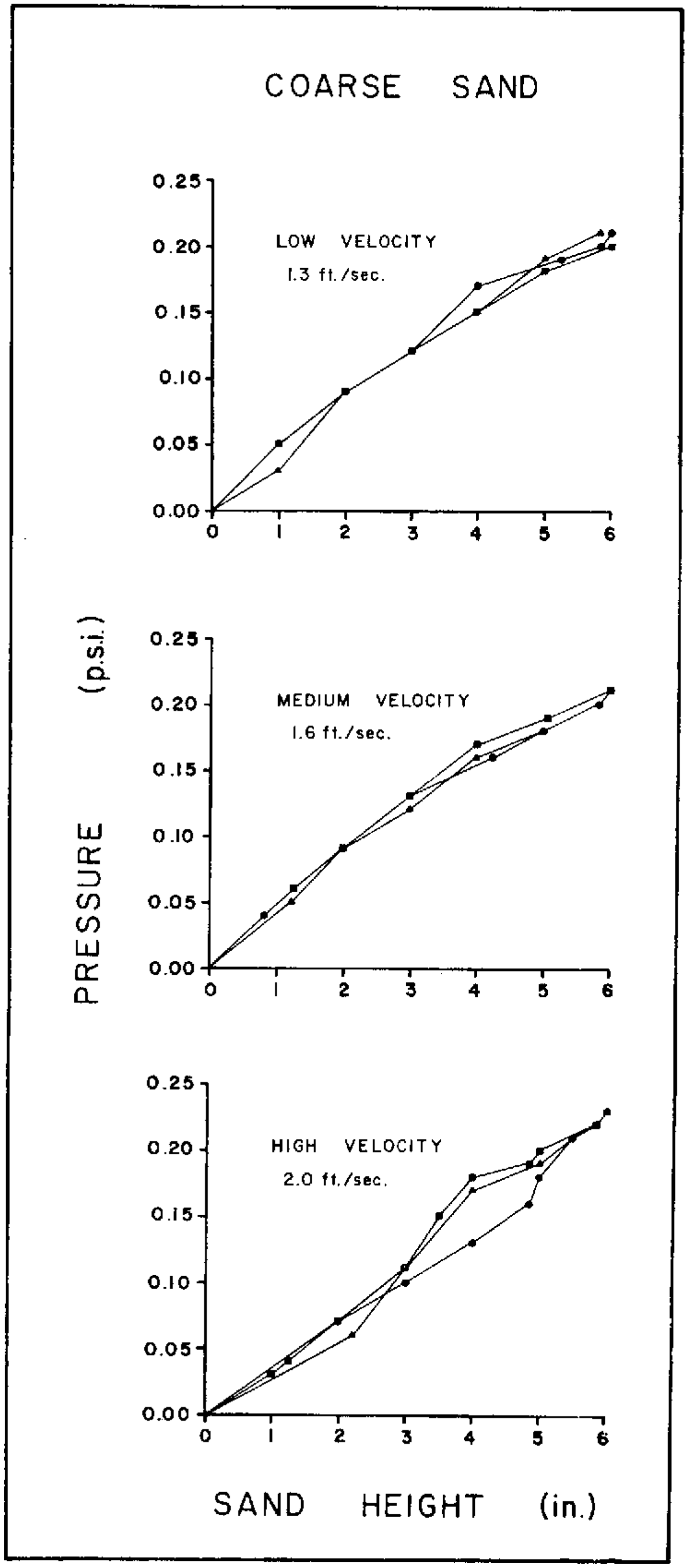

COARSE SAND
LOW VELOCITY
1.3 ft./sec.
MEDIUM VELOCITY
1.6 ft./sec.
HIGH VELOCITY
2.0 ft./sec.
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
0.25
0.20
0.15
0.10
0.05
0.00
0 1 2 3 4 5 6

Figure 9. Single-gage dynamic loading tests of bed forms, composed of the moderately well-sorted medium sand, conducted at three different flow velocities. Three replicate trials of each test conducted for dispersion evaluation.

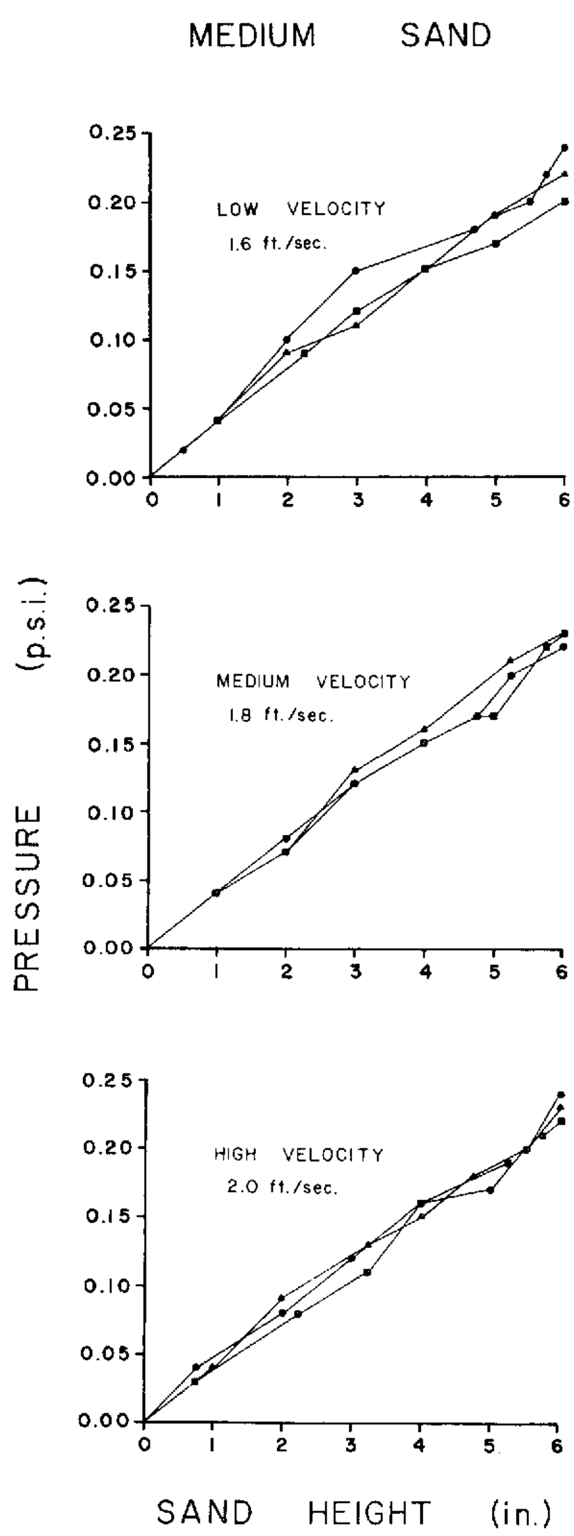
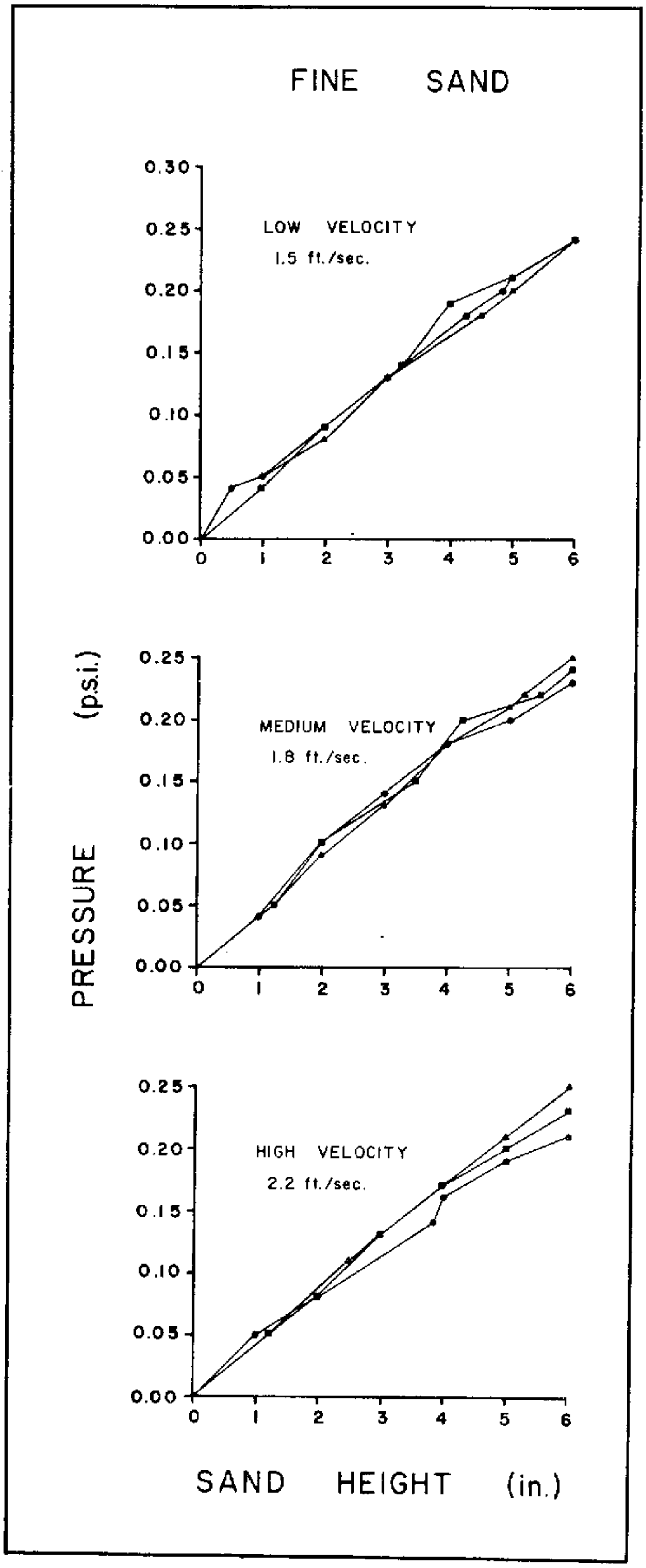

MEDIUM SAND
LOW VELOCITY
1.6 ft./sec.
MEDIUM VELOCITY
1.8 ft./sec.
HIGH VELOCITY
2.0 ft./sec.
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
0.00
0.05
0.10
0.15
0.20
0.25
0
1
2
3
4
5
6

Figure 10. Single gage dynamic loading test of bed forms composed of well-sorted fine sand, conducted at three different flow velocities. Three replicate trials of each test conducted for dispersion evaluation.


FINE SAND
LOW VELOCITY
1.5 ft./sec.
MEDIUM VELOCITY
1.8 ft./sec.
HIGH VELOCITY
2.2 ft./sec.
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
1
2
3
4
5
6

In general, the flow velocity and migration rates of coarse-grained bed forms appear to have no significant effect on gage response. A comparison of the coarse-grained dynamic and static tests illustrates that for a 5-inch sand height, dynamic loading results in an average pressure of 0.18 p.s.i., compared with 0.23 p.s.i. for agitated static loading. This 22 percent pressure reduction indicates less settling and looser packing, resulting in a lower density associated with migrating bed forms than with artificially sprinkled sand which has moderately settled and compacted. The absolute values of the pressure differential would be largely reliant upon the amount of static agitation and length of settling time.

Medium-grained bed forms. The results of dynamic testing for bed forms composed of the moderately well-sorted medium test sand are presented in Figure 9. The three velocity tests all illustrate essentially linear response curves, with the low velocity curves suggesting some curvilinear tendencies at sand heights greater than 3 inches. The three replicate trials for each velocity test show the lowest dispersion and best reproducibility for high velocity flow (± 8%), the poorest reproducibility for low velocity flow (± 17%), and an intermediate degree for medium velocities (± 13%). This is in contrast with the relative dispersions exhibited by coarse-grained bed forms, where the poorest reproducibility occurred during the high velocity runs; this inconsistency suggests that velocity alone is not the sole factor controlling dispersion, but that velocity and grain texture are jointly influential. The optimum velocity for minimal dispersion may well be a complex function of sediment size and sorting characteristics.

Pressure differentials between the three velocity tests are not significantly different, indicating that flow velocity and migration rates of medium-grained bed forms have no apparent influence on gage response. A comparison of the medium-grained dynamic and static tests illustrates that for a 5-inch sand height, dynamic loading once again results in an average pressure of 0.18 p.s.i., compared with 0.20 p.s.i. for the agitated static loading. This 10 percent pressure reduction indicates the looser packing arrangement and lower density of the migrating bed forms, and is in agreement with the results illustrated by the coarse-grained bed forms.

Fine-grained bed forms. The dynamic testing results for bed forms composed of the well-sorted fine sand are presented in Figure 10. The three velocity tests all illustrate linear pressure-sand height response curves. In full agreement with results from the coarse-grained bed forms, the lowest dispersion and best reproducibility was obtained by medium velocity flow (± 8%), whereas the poorest was obtained by the high velocity flow (± 16%); low velocity flow produced an intermediate degree of reproducibility (13%). The influence of velocity on gage response, as indicated by pressure differentials among the three velocity tests, is of minor significance. The only observable difference is that the high velocity curves exhibit slightly lower pressures than the medium velocity curves within the middle portion of the response range. However, no significant differential occurs between the high and low velocity tests, where contrasts should be most apparent if velocity were an influential factor. A comparison of the fine-grained dynamic and static tests illustrate that for a 5-inch sand load, the average dynamic loading pressure is 0.20 p.s.i. compared to 0.22 p.s.i. for static loading. This 10 percent pressure reduction indicates looser packing and lower density in the migrating fine-grained bed forms, which is consistent with results obtained for both the coarse and medium-grained bed forms.

In general, the entire series of single-gage dynamic tests using the three test sands indicate that flow velocity and migration rates of varying-textured bed forms appear to have no significant influence on gage response characteristics. The major source of response dispersion appears to be inconsistencies in packing and density associated with migrating bed forms. These inconsistencies result from both sorting variability within bed forms, as well as differential settling and compaction during transport.

Multiple-Gage System

The objectives of the dynamic tests conducted on the multiple gage system were to determine if several gages operating simultaneously could function as an effective array system, and to augment response data obtained from the single-gage tests. Results of the multiple-gage tests are presented in Figures 11-14.

Relative gage response. The overall pressure response for each gage comprising the array system is illustrated by superimposed response envelopes for each of the three test sands employed (Fig. 11-12). Each envelope denotes the total combined response dispersion experienced by a gage for a particular test

Figure 11. Response envelopes for individual array gages showing textural effects resulting from the three test sands. Each envelope is based on 9 flume tests conducted at all velocities.

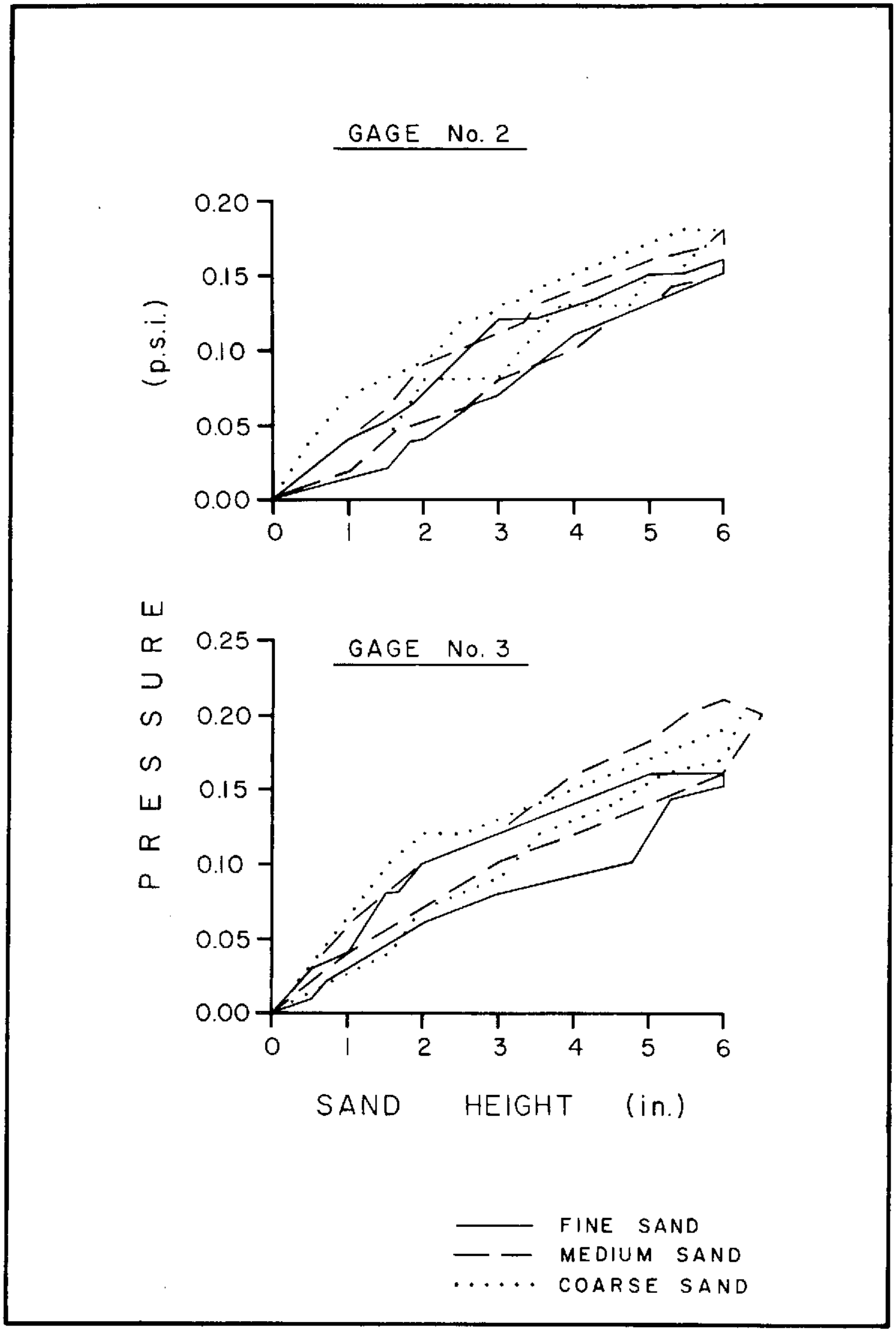
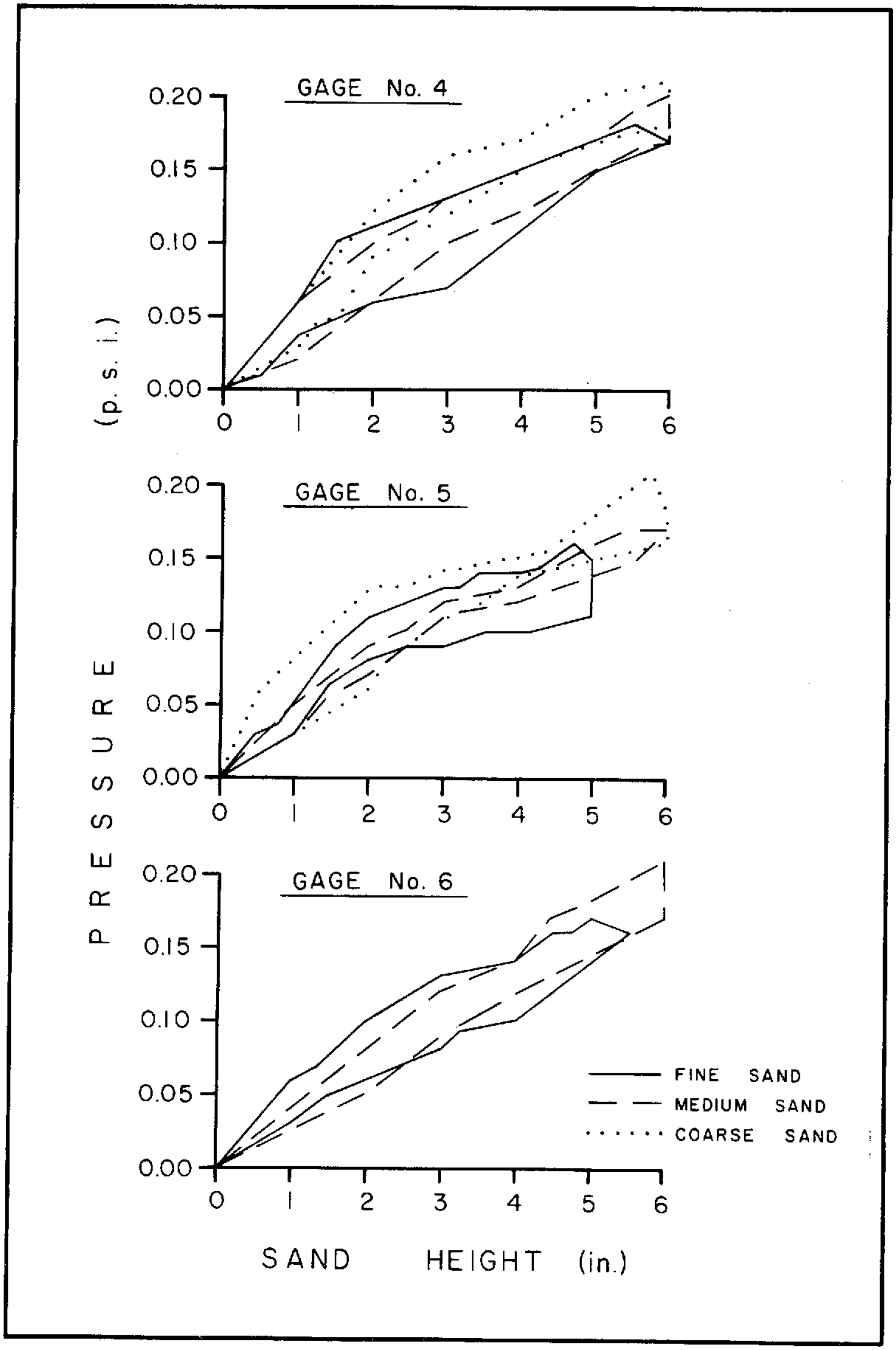

GAGE No. 2
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
6
(p.s.i.)
PRESSURE
GAGE No. 3
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
6
SAND HEIGHT (in.)
FINE SAND
MEDIUM SAND
COARSE SAND

Figure 12. Response envelopes for individual array gages showing textural effects resulting from the three test sands. Each envelope is based on 9 flume tests conducted at all velocities.



GAGE No. 4
GAGE No. 5
GAGE No. 6
PRESSURE (p. s. i.)
0.00
0.05
0.10
0.15
0.20
0
1
2
3
4
5
6
SAND HEIGHT (in.)
FINE SAND
MEDIUM SAND
COARSE SAND

Figure 13. Response envelopes for individual array gages illustrating differential effects of dynamic loading vs. unloading conditions. Envelopes are based on all conducted flume tests.

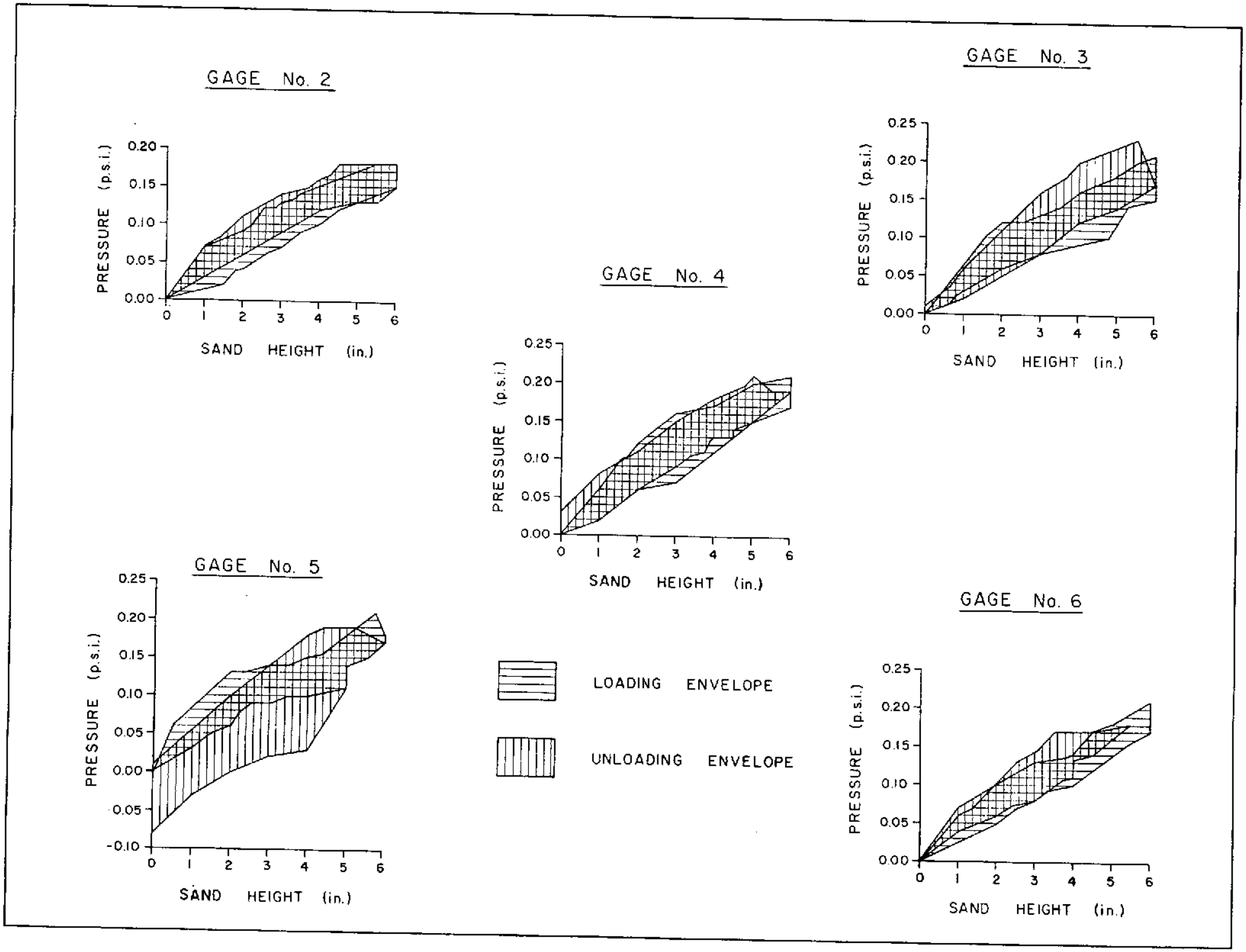
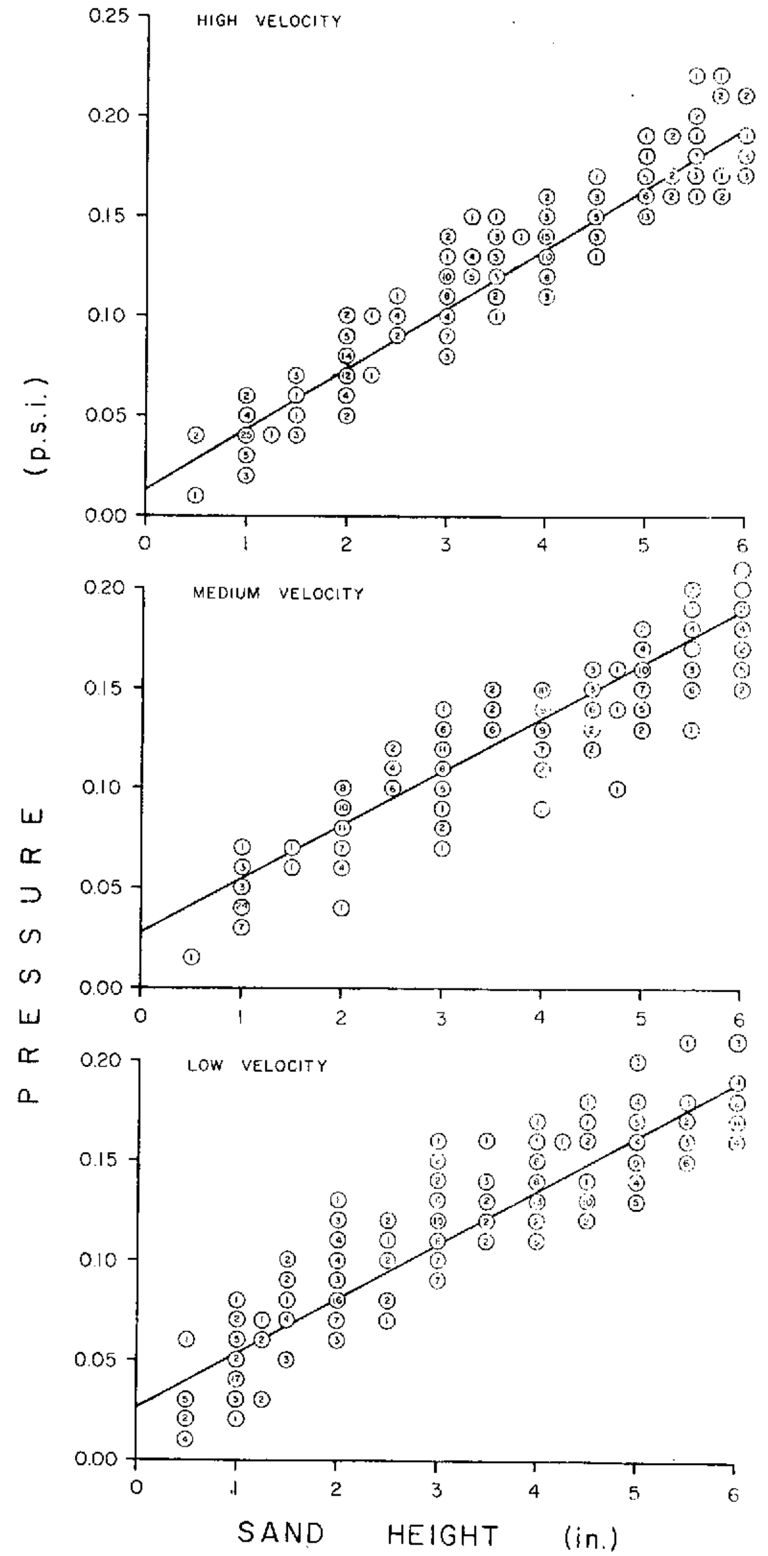

GAGE No. 2
PRESSURE (p.s.i.)
0.20
0.15
0.10
0.05
0.00
0 1 2 3 4 5 6
SAND HEIGHT (in.)
GAGE No. 3
PRESSURE (p.s.i.)
0.25
0.20
0.15
0.10
0.05
0.00
0 1 2 3 4 5 6
SAND HEIGHT (in.)
GAGE No. 4
PRESSURE (p.s.i.)
0.25
0.20
0.15
0.10
0.05
0.00
0 1 2 3 4 5 6
SAND HEIGHT (in.)
GAGE No. 5
PRESSURE (p.s.i.)
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
0 1 2 3 4 5 6
SAND HEIGHT (in.)
LOADING ENVELOPE
UNLOADING ENVELOPE
GAGE No. 6
PRESSURE (p.s.i.)
0.25
0.20
0.15
0.10
0.05
0.00
0 1 2 3 4 5 6
SAND HEIGHT (in.)

Figure 14. Scatter diagrams illustrating total system response, as a function of velocity. Numbers indicate occurrence frequency of specific pressure values, which are fitted with least-squares regression lines.


HIGH VELOCITY
MEDIUM VELOCITY
LOW VELOCITY
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
0.25
0.20
0.15
0.10
0.05
0.00
0 1 2 3 4 5 6

sand at all three flow velocties, each with its three replicate trials; therefore, each grain-size envelope reflects the total dispersion generated during 9 flume tests.

Using envelope midpoints at a 5-inch sand height as reference points, the relative positions of the midpoints are essentially the same for all gages. The moderately-sorted coarse sand envelope exhibits the highest pressure, whereas the well-sorted fine sand envelope exhibits the lowest value. This relationship is consistent with results obtained from the static tests, and illustrates that the relative responses to sediment texture are the same for all gages comprising the array. However, absolute pressure values within each response envelope, as well as pressure differentials between envelopes, are variable among the different gages; this illustrates the necessity for each gage comprising an array system to employ its own unique set of calibration curves.

The composite dispersion that results from combining the superimposed grain-size envelopes is variable among the different array gages. The lowest degree of composite dispersion and best resulting reproducibility is exhibited by gage #6 which is based on only two grain-size envelopes; the highest dispersion and poorest reproducibility is exhibited by gage #4. Reproducibility values for the individual array gages are as follows: gage #2 (± 33%), gage #3 (± 37%), gage #4 (± 43%), gage #5 (± 33%), gage #6 (± 25%). These values indicate the relative effectiveness of the individual gages. In addition, they illustrate the poor overall reproducibility of gages when subjected to variable sand textures, a situation most likely to occur under natural field conditions. Therefore, these tests illustrate a major quantitative limitation of the evaluated multiple-gage system.

The response characteristics of the individual array gages were further evaluated in terms of dynamic loading versus dynamic unloading conditions. It was believed that erosional and accretionary processes may have different effects on sediment packing and density, thus possibly increasing the degree of dispersion. Consequently, loading and unloading envelopes were compared for each array gage (Fig. 13). Each envelope encompasses all flume tests conducted for the three test sands at all velocities, under either loading or unloading conditions; therefore, each envelope indicates that for equivalent sand heights, there are some gage response differences between erosional and accretionary processes, as indicated by envelope displacements.

Systematic displacements are most apparent on gages #2 and #6, where the unloading envelope is largely displaced toward higher pressures. This could be attributed to a tighter packing arrangement induced by the higher velocity scouring currents, as opposed to depositional currents. In contrast, gage #5 exhibits a systematic displacement of the unloading envelope toward lower pressures. This enigmatic displacement might be attributed to a defective gage; the gage was characterized by erratic behavior throughout the unloading tests by failing to return to its initial zero position.

The net result of comparing dynamic loading and unloading conditions was to further reduce the overall reproducibility of the array gages, by increasing the gages' composite dispersion range to encompass both erosional and accretionary processes - a normal situation under natural field conditions. The composite dispersion for both loading and unloading envelopes results in the following overall reproducibility values for the array gages: gage #2 (± 40%), gage #3 (± 50%), gage #4 (± 44%), gage #5 (± 48%), gage #6 (± 36%). These poor overall reproducibility values for the array gages further emphasize the extreme quantitative limitations of the evaluated multiple-gage system.

Total system response. The total overall response dispersion of the entire multiple-gage system, as a function of velocity, is illustrated by Figure 14. These scatter diagrams are based on the entire sequence of dynamic tests conducted at the three velocities, employing all array gages and all test sands. The encircled numbers refer to the frequency that a particular pressure value was recorded. Linear regression lines were fitted to these points, using the least-squares method. The correlation coefficients for the low, medium, and high velocities were calculated to be 0.91, 0.93, and 0.95, respectively. All three regression lines have nearly the same slope (0.54, 0.54, and 0.60) for the low, medium, and high velocity tests, respectively. These regression analyses indicate that under all dynamic conditions tested, there is a strong direct relationship between pressure and sand height. In addition, the analyses indicate that tested flow velocity and bed form migration rates have no significant influence on gage response. Therefore, the array system could be utilized in a wide variety of natural hydraulic environments. The main limiting factor of the system is the high gage response dispersion and poor reproducibility, which appears to be relatively consistent for the three flow velocities.

Field Testing

Upon completion of laboratory testing, both the single-gage and multiple-gage systems were field-tested to evaluate their performance under natural conditions. The systems were evaluated in terms of their response characteristics and operating durability. In contrast to laboratory response curves based on absolute pressure values, the field response curves are based on relative pressure fluctuations from an arbitrary zero reference pressure; this reference pressure is set according to the initial gage burial depth within the beach foreshore. Positive or increasing pressures as a function of time indicate sediment accretion; whereas, negative or decreasing pressures indicate erosion. Absolute values of pressure are dependent upon specific gage sensitivity settings on the recorder, and are not indicative of absolute sand-height values. Gage sensitivities were frequently changed to provide optimum recorder deflection.

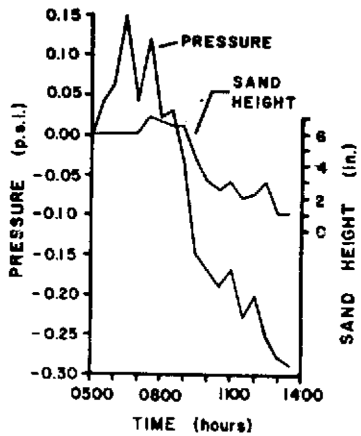
Single-Gage System

Initial field testing was conducted with the single-gage system to evaluate its performance as a simple point sensor. Five separate tests were conducted (Fig. 15). The first set (August 29, 1972) was performed along the beach sector off Camp Pendleton, whereas the remaining four tests were conducted along the beach sector off the Dam Neck Naval Base (Fig. 4). The following is a brief description of each field test.

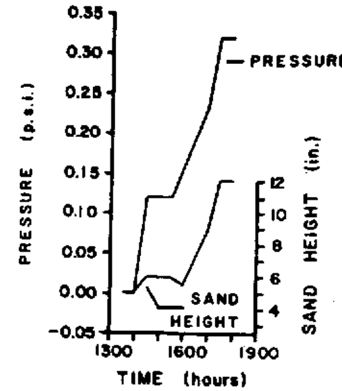
August 29, 1972 - During this initial 9-hour test, the beach experienced 5 inches of net erosion. The test commenced at low tide (0514 DST), with the gage implanted to a depth of 5.75 inches; high tide occurred at 1143. The initial gage response is an abrupt increase in pressure attributed to the initial settling and compaction of the burial sand replaced after gage implantation. This "settling effect" stabilized within two hours, after the burial sand achieved equilibrium with the undisturbed beach sand; this initial settling phase was also noted on most subsequent field tests when sand heights remained fairly constant during the first two-hour period. After initial settling, the beach experienced a brief accretionary episode, followed by an extended period of erosion. This long period trend was accurately denoted by the gage response curve. In a study of foreshore sedimentation, Strahler (1966) developed a model beach

Figure 15. Single-gage field test results showing gage responses and corresponding sand height fluctuations.

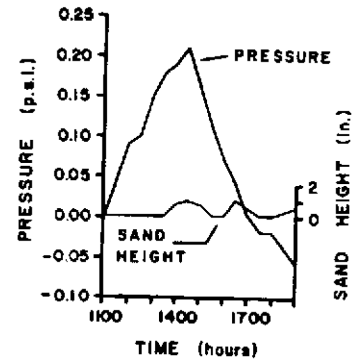
AUGUST 29



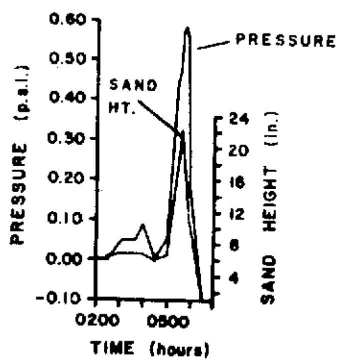
JANUARY 15



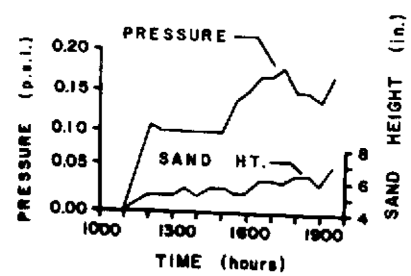
JANUARY 30



FEBRUARY 4



FEBRUARY 13



cycle of erosion and accretion that is regulated by the semidiurnal tidal cycle. In Strahler's cycle, a rising flood tide induces a brief small-scale phase of initial deposition, followed by a brief small-scale scour phase; these phases are followed by a longer large-scale "step deposition phase" which continues until approximately high tide. During the subsequent ebb tide, the deposited "step sediment" is progressively removed by migrating seaward with the falling tide. The beach trend observed during this field test may reflect parts of Strahler's model cycle.

During this test, the gage was sequentially subjected to the hydraulic regimes of the swash-backwash zone, surf zone, and breaker zone. It became evident that the sand gage was also sensitive to the hydraulic impact of the impinging surf and breakers. This resulted in large-scale excursions of the recorder pen with each impact, thus making identification of the main trend line difficult. Although the gage is insensitive to pressure variations within the hydraulic column itself, the abrupt response pressure increases may have been partially attributed to impact-induced sediment compaction. This "hydraulic noise" was substantially reduced during subsequent tests by the installation of a high-frequency filter network within the recorder unit.

January 15, 1973 - During this brief 4-hour test, the beach experienced 7 inches of net accretion. After commencing the test at low tide (1031 EST), moisture contamination occurred at the extension cable connection; this resulted in a delay of three hours. By this time, the tidal level had risen several inches, and the sand gage was then buried to a depth of 5 inches. However, gage submergence never progessed beyond the upper reaches of the surf zone; high tide occurred at 1620. Even under these conditions, a significant amount of continued accretion did occur, and the gage accurately delineated this accretionary trend.

January 30, 1973 - During this 8-hour test, which commenced at low tide (1107), only 0.5 inch of net accretion occurred because of light surf conditions; high tide occurred at 1654. The initial gage burial depth was 7 inches. Only two short-period sand height fluctuations occurred, neither of which were accurately delineated by gage response. Long-period trend correspondence is poor, with an anomalous high-pressure response associated with no significant sand accretion. This anomaly may be partially attributed to the initial "settling effect"; however, its magnitude and duration suggest an additional long-term causative factor, possibly a ground water effect. As noted by Grant (1948), escaping ground water in the effluent zone of the foreshore has a dilating effect on sediment; this would tend to reduce packing and sediment density. Consequently, a fluctuating water table along a beach experiencing a semidiurnal tidal cycle could produce variable dilation effects that might result in density variations with time. The high pressure anomaly observed in this test could thus be explained by a decrease in dilation associated with a falling water table lowered below the gage level, followed by increasing dilation associated with a rising water table above the gage level during flood tide. If this hypothesis is valid, it would illustrate a major limitation of the gage, namely, its inability to differentiate between sand-height effects and ground water effects.

February 4, 1973 - This brief 4-hour test commenced at low tide (0200), with the beach experiencing about 3 inches of net erosion; high tide occurred at 0840. The gage was initially buried 6 inches, and accurately delineated the subsequent beach trend. The trend consists of a sequence of minor accretion, followed by minor erosion, and finally major "step" deposition. This trend correlates reasonably well with Strahler's (1966) model cycle, and the "step" deposits were actually observed by the field crew as they progressively migrated up the foreshore. Step deposition began shortly after 0500, and resulted in 11 inches of sand accretion within a 45-minute period. Unfortunately, this test was terminated early when the cable was ripped apart from the gage housing by the strong longshore current.

February 13, 1973 - The final test utilizing the single gage system was an 8 1/2-hour test, during which time the beach experienced 3 inches of net accretion. The test commenced slightly after low tide (1040), with an initial gage burial depth of 4 inches; high tide occurred at 1610. This test occurred three days after a severe storm had cut an 8 ft. escarpment along the adjacent dune line. It was necessary to move the test site 300 feet to the south of the regular station, in order to insure protection of the tent and the equipment. During this test, steel wickets were used for the first time to secure the cable in position, and the technique proved successful. The beach experienced a general long-period accretionary trend, with numerous short-period fluctuations. The gage response curve delineates the trend, but does not accurately depict the short-period fluctuations. The sharp initial rise in pressure probably reflects the initial settling effect.

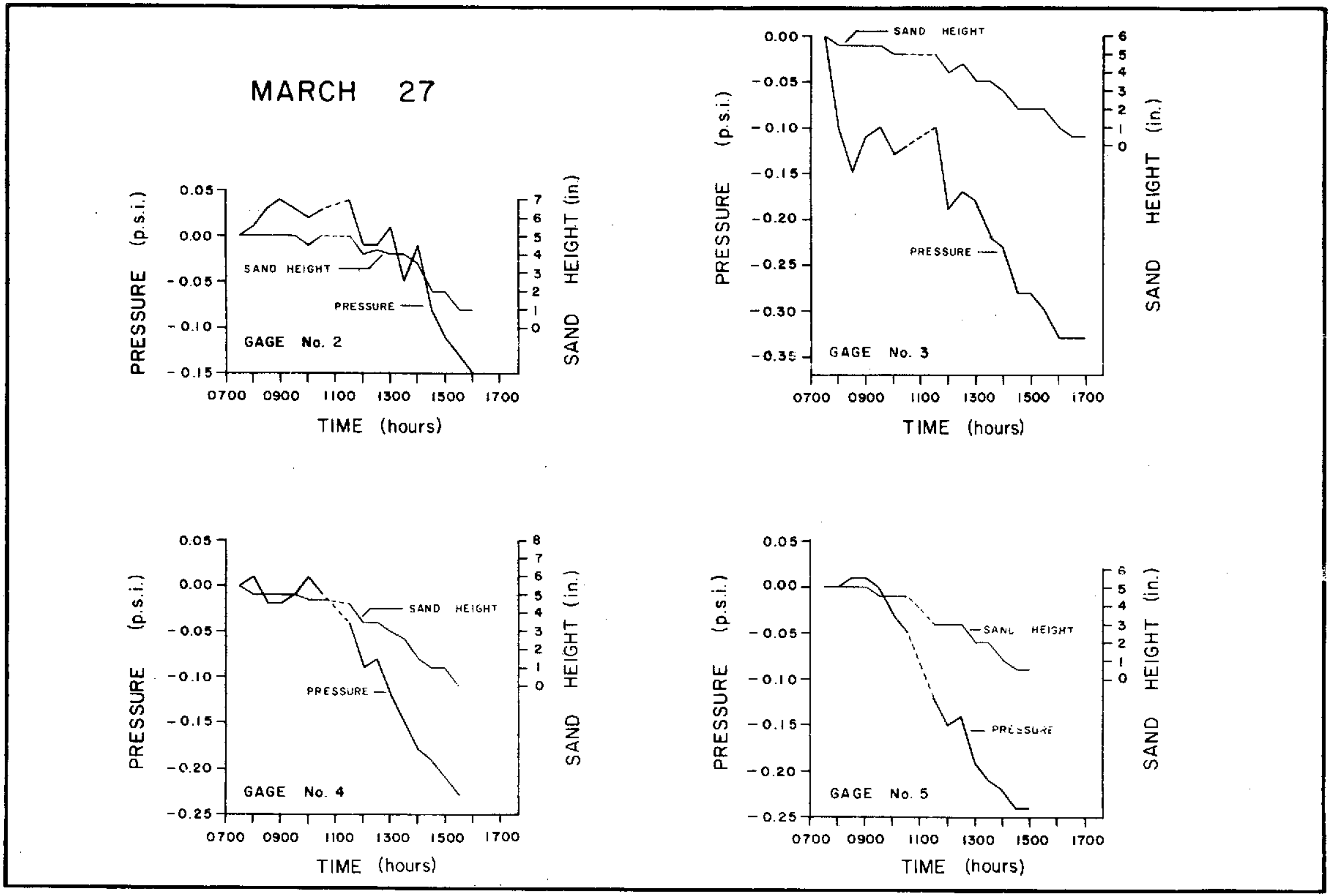
The foregoing single-gage field tests were conducted as a prelude to the field testing of the multiple-gage array system. The tests indicate that the single-gage system can be an effective point sensor in delineating long-period beach sedimentation trends. However, several system failures indicate that the system's components are not sufficiently durable for extended field operations.

Multiple-Gage System

The field testing of the multiple-gage system was conducted to evaluate its performance as an areal sensor. Six separate tests were conducted, all of which were located along the beach sector off Dam Neck Naval Base (Fig. 4). All gages were not continuously operable during the entire sequence of tests; consequently, variable numbers of gages were utilized during individual tests. A brief description of each field test follows.

March 27, 1973 - This initial multiple-gage test lasted 9 hours, and consisted of a 4-gage array (Fig. 16). The test commenced at low tide (0737), with gage burial depths ranging from 4.5 to 6.0 inches; high tide occurred at 1335. The long-period sand height trends are similar at all four gage sites, and consist of continued erosion, with net amounts ranging from 4.0 to 5.5 inches at the individual sites. Superimposed on these long-period trends are short-period sand height fluctuations which are variable among gage sites. The four gage response curves all successfully denote the long-period erosional trends, although response curve amplitudes are variable, depending on individual gage sensitivity. However, the gage response curves are not fully reliable in accurately denoting short-period sand fluctuations. Some of the short-period gage responses appear to be extraneous fluctuations, possibly caused by hydraulic impact. This might be illustrated by the abrupt pressure increase that occurred on all gages at about 1230. This pressure increase correlates with minor accretion at gage site #3, but not at gage sites #2, 4, and 5. The presence of this fluctuation on all gage response curves indicates a common causative factor,

Figure 16. Field tests results of multiple-gage system; March 27, 1973. Individual gage response curves and corresponding sand height fluctuations are illustrated.



MARCH 27
GAGE No. 2
GAGE No. 3
GAGE No. 4
GAGE No. 5
SAND HEIGHT
PRESSURE
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
TIME (hours)
0700 0900 1100 1300 1500 1700

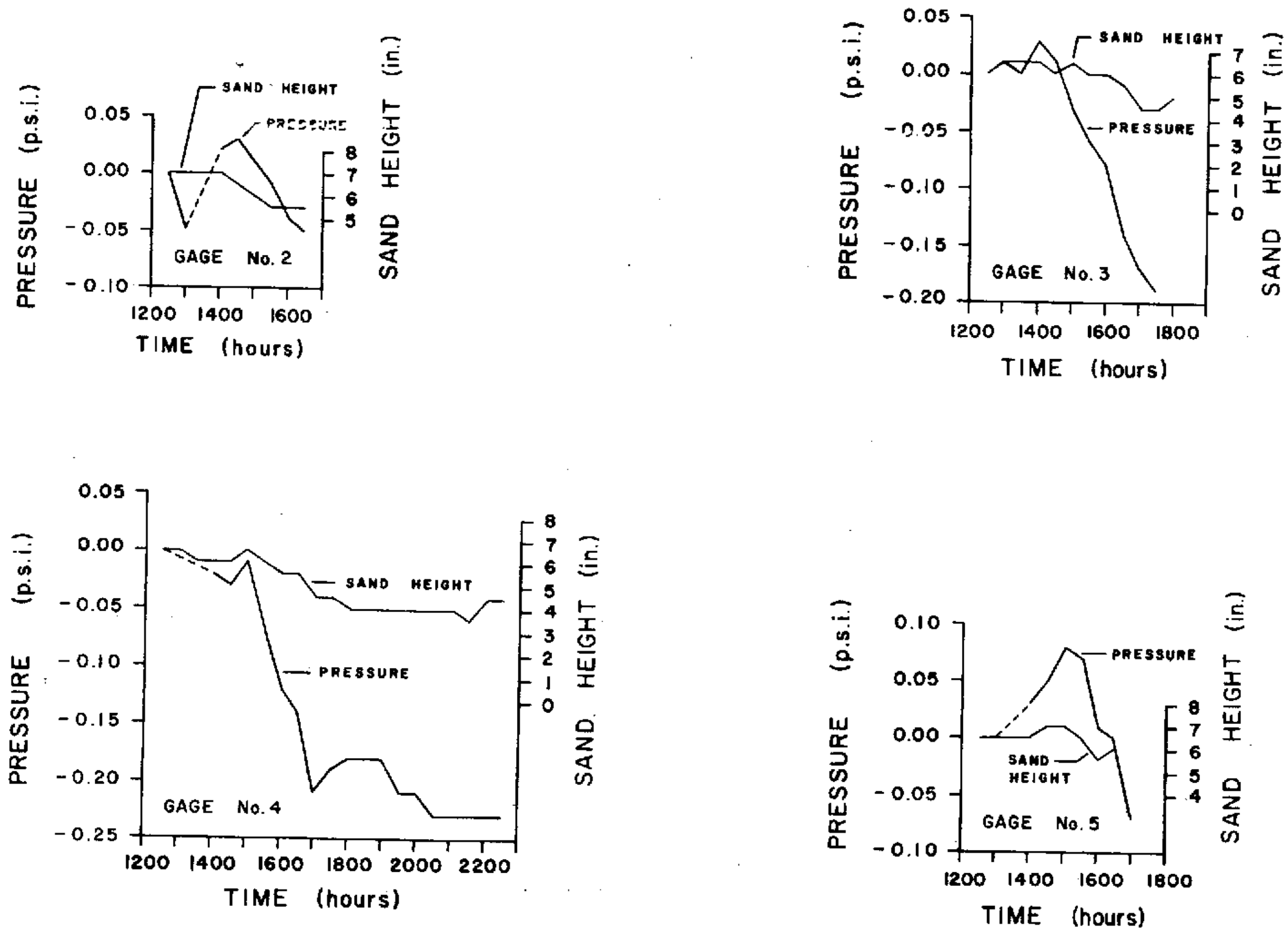
possibly hydraulically-induced compaction resulting from the impact of an unusually large wave or heavy surf. The variations in short-period gage response among the four sites may actually reflect the combined effects of real small-scale differences in sand height, in conjunction with variations in the intensity of hydraulically-induced pressures among the different gage sites. This would suggest a major limitation of the system in accurately denoting short-period sand height variations; whereas, its long-period response is quite reliable.

<u>April 1, 1973</u> - This was a 10-hour test that employed a 4-gage array (Fig. 17). The test commenced shortly after low tide (1150), with gage burial depths within the 6-7 inch range; high tide occurred at 1802. The long-period sand height trends are similar at all four gage sites, consisting of general net erosion ranging from 0.5 to 2.0 inches. Short-period sand fluctuations are also present and variable among the four sites. During this test, an unusually strong longshore current (141 ft./min.) damaged three cables, rendering gages #2, 3, and 5 inoperative after five hours. This cable-breakage problem was somewhat reduced on subsequent tests by burying the cables. During their course of operation, the gages adequately responded to the long-period erosional trends, but were not reliable for short-period fluctuations. Best results were obtained with gage #4 which was in longest operation.

<u>April 8, 1973</u> - This 10 1/2-hour test employed a 5-gage array (Fig. 18). The test commenced at low tide (0518), with gage burial depths in the 5.5 to 7.0 inch range; high tide occurred at 1116. Similar long-period sand height trends are present at all gage sites, and consist of general net erosion ranging from 4.5 to 6.5 inches. Superimposed short-period fluctuations are also present and variable among the gage sites. Regarding gage response pressure, this was one of the most successful field tests conducted. All gages show excellent response correlations with the long-period trends, as well as good correlations with many of the short-period fluctuations. This is especially well illustrated by gages #2 and 4. In this test, there appears to be a minimum of extraneous hydraulically-induced responses, possibly because of the effective filtering of relatively high frequency ambient hydraulic components. This test indicates the desirability of a variable filter network within the recorder, which can be adjusted for optimum filtration of the variable hydraulic frequencies experienced during field operations.

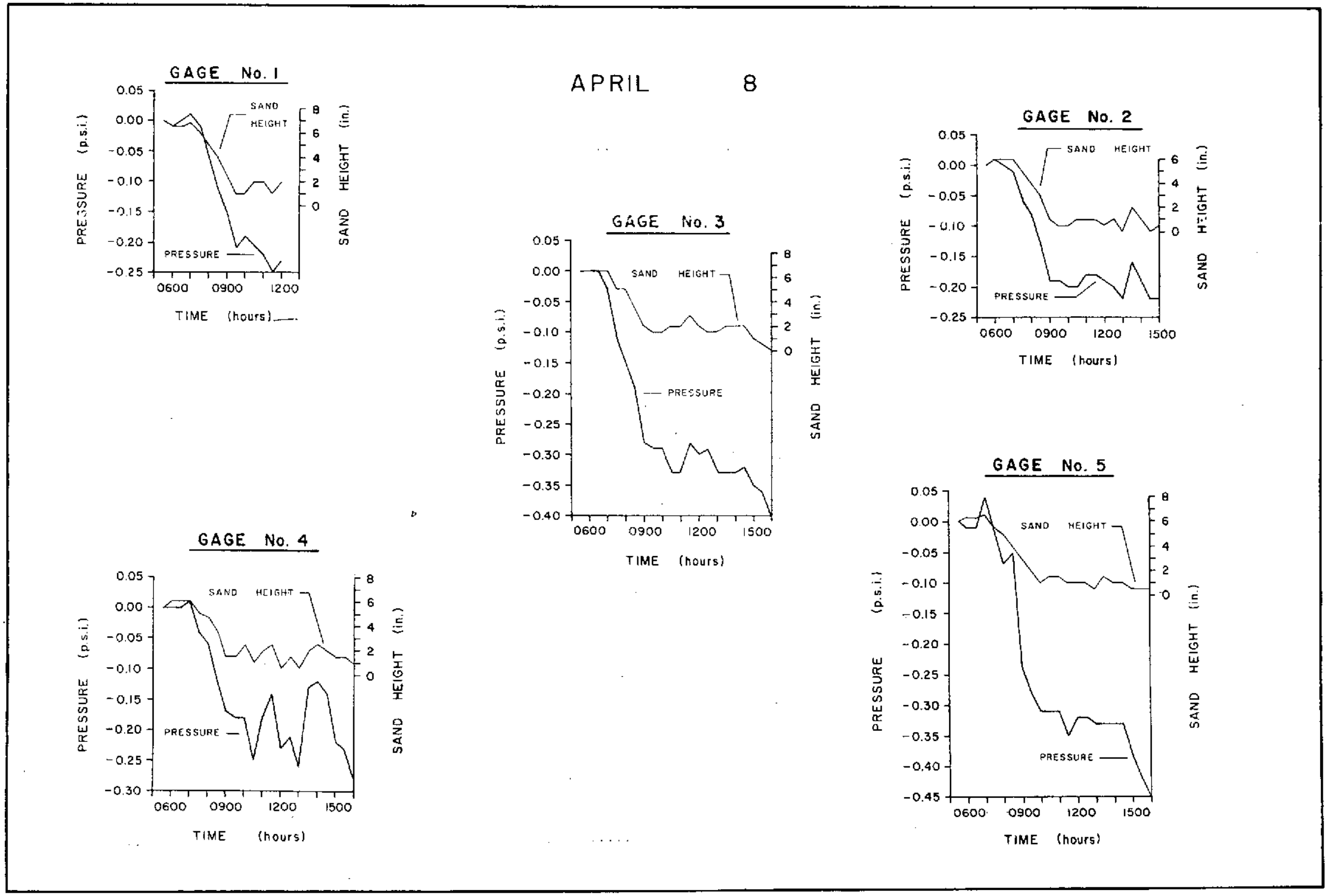
Figure 17. Field results of multiple-gage system; April 1, 1973. Individual gage response curves and corresponding sand height fluctuations are illustrated.

APRIL 1


SAND HEIGHT
PRESSURE
GAGE No. 2
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
TIME (hours)
SAND HEIGHT
PRESSURE
GAGE No. 3
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
TIME (hours)
SAND HEIGHT
PRESSURE
GAGE No. 4
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
TIME (hours)
PRESSURE
SAND HEIGHT
GAGE No. 5
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
TIME (hours)

43-A

Figure 18. Field results of multiple-gage system; April 8, 1973. Individual gage response curves and corresponding sand height fluctuations are illustrated.


APRIL 8
GAGE No. 1
GAGE No. 2
GAGE No. 3
GAGE No. 4
GAGE No. 5
SAND HEIGHT
PRESSURE
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
TIME (hours)
0600
0900
1200
1500

April 13, 1973 - This 9 1/2-hour test employed a 5-gage array (Fig. 19). The test commenced about 1 1/2 hours after low tide (1016), with gage burial depths in the 9-11 inch range; high tide occurred at 1613. Similar long-period sand height trends occur at all gage sites, and consist of a cyclic pattern of accretion and erosion. Net changes among the sites are variable, ranging from 2.5 inches of erosion to 0.5 inches of accretion. This cyclic pattern, as well exemplified at the gage site #5, may correlate with phases of Strahler's (1966) beach cycle. All gage response curves exhibit good long-period trend correlations, resulting in one of the more successful field tests; however, the short-period responses are not highly reliable.

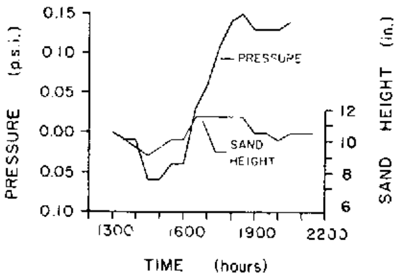
April 27, 1973 - This 10-hour test employed a 6-gage array system (Fig. 20). The test commenced about one hour after low tide (0744), with gage burial depths in 7-9 inch range; high tide occurred at 1354. No significant long-period sand height trends were noted at the gage sites during this test, since very little sediment migration occurred. Net changes at the individual stations ranged from 0.5 inch of erosion to 1.0 inch of accretion. Short-period fluctuations are present, and somewhat variable among the gage sites. Overall gage response for this test was poor; all gages operated highly erratically during the test, possibly as the result of moisture seepage in the cables of a fluctuating power supply.

April 30, 1973 - This final 11 1/2-hour field test of the multiple-gage system used a 5-gage array, and was perhaps the most successful and encouraging test of the entire series (Fig. 21). The test commenced at low tide (1211), with gage burial depths in the 6.5-8.0 inch range; high tide occurred at 1828. Similar long-period sand height trends are present at all gage sites, and consist of a well-developed sinusoidal 2-cycle accretion-erosion sequence. This cyclic trend appears to correlate well with Strahler's (1966) four-phase beach cycle. All gage sites experienced net erosion, ranging from 0.5 to 2.0 inches. The response curves for all gages exhibit excellent correlation with the long-period cyclic trends. In addition, they also exhibit fairly good short-period correlations, with a minimum of extraneous pressure responses. This test well illustrates the potential of the multiple-gage system as a qualitative tool for studying long-period sediment migration trends.

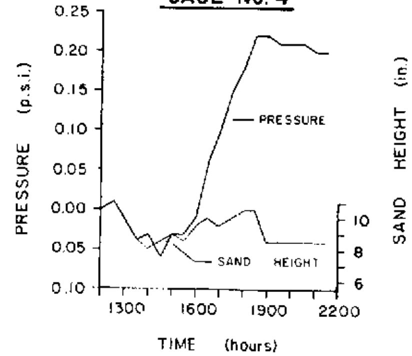
Figure 19. Field results of multiple-gage system; April 13, 1973. Individual gage response curves and corresponding sand height fluctuations are illustrated.

APRIL 13

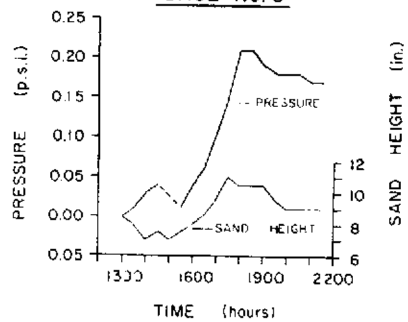
GAGE No. 2



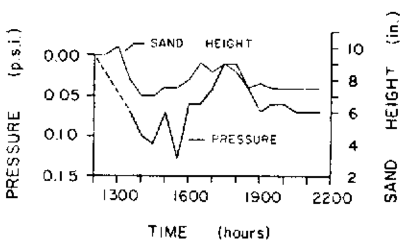
GAGE No. 4



GAGE No. 3



GAGE No. 5



GAGE No. 6

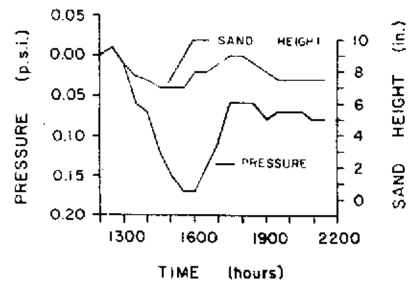
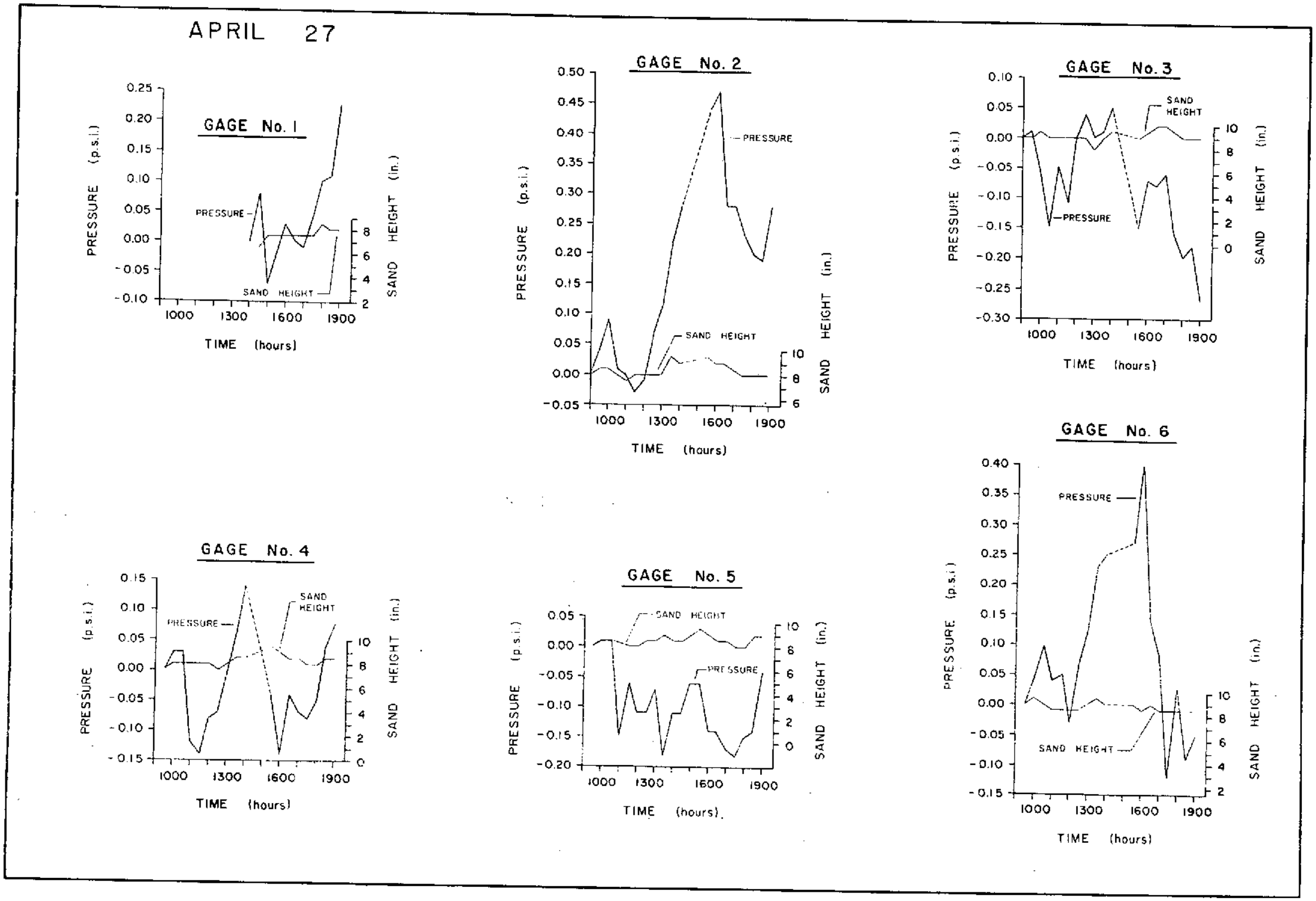


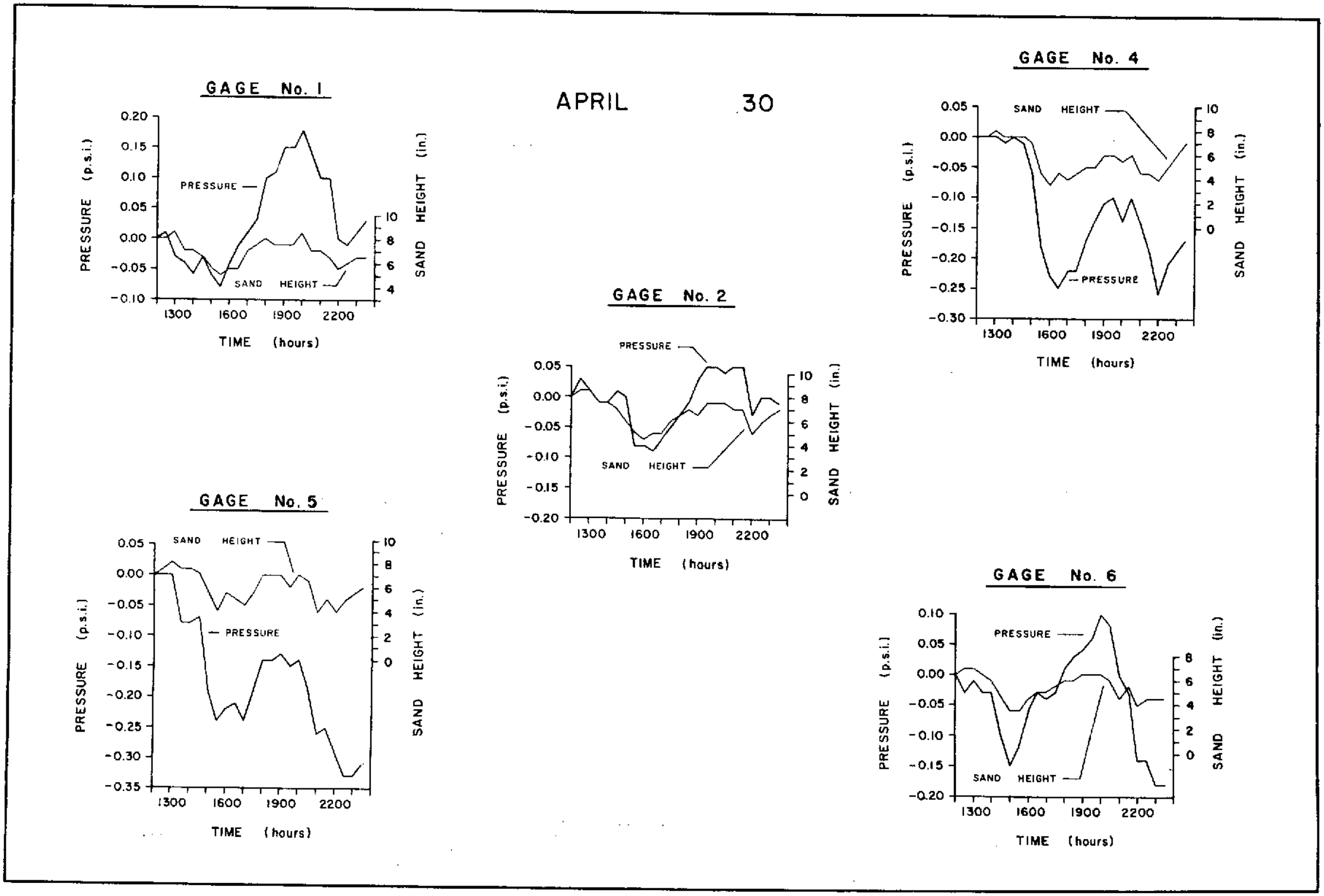
Figure 20. Field results of multiple-gage system; April 27, 1973. Individual gage response curves and corresponding sand height fluctuations are illustrated.



APRIL 27
GAGE No. 1
GAGE No. 2
GAGE No. 3
GAGE No. 4
GAGE No. 5
GAGE No. 6
PRESSURE
SAND HEIGHT
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
TIME (hours)
1000
1300
1600
1900

47-A

Figure 21. Field results of multiple-gage system; April 30, 1973. Individual gage response curves and corresponding sand height fluctuations are illustrated.


APRIL 30
GAGE No. 1
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
PRESSURE
SAND HEIGHT
TIME (hours)
GAGE No. 2
PRESSURE
SAND HEIGHT
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
TIME (hours)
GAGE No. 4
SAND HEIGHT
PRESSURE
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
TIME (hours)
GAGE No. 5
SAND HEIGHT
PRESSURE
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
TIME (hours)
GAGE No. 6
PRESSURE
SAND HEIGHT
PRESSURE (p.s.i.)
SAND HEIGHT (in.)
TIME (hours)

CONCLUSIONS AND RECOMMENDATIONS

Static loading tests conducted on the single-gage system result in good linear pressure response up to a 24-inch sand height. The tests further indicate that absolute pressure values are influenced by sediment texture, which affects sediment packing and porosity. Grain uniformity is the most influential factor, with poorer-sorted sediments exhibiting lower porosity and producing higher response pressures; the influence of grain size is of relatively minor significance. The amount of response dispersion and degree of reproducibility is a function of packing and porosity consistency, which is also influenced by sediment texture. The coarser-grained and better-sorted sediment tend to produce more consistent responses, resulting in minimal dispersion. The static tests further indicate that the degree of compaction is highly influential in determining absolute response pressures, as well as the amount of response dispersion. Increasing compaction produces progressively tighter and more systematic packing arrangements, resulting in progressively higher response pressures and lower dispersion. The influence of both sediment texture and compaction on gage response illustrates a major quantitative limitation of the strain-gage technique for monitoring sand heights. Under natural field conditions, these response effects would not be distinguishable from pressure responses resulting from sand-height variations.

Dynamic loading tests conducted on both the single-gage and multiple-gage systems illustrate that gage response up to a 6-inch sand load is not significantly influenced by either hydraulic flow velocity or the migration rates of varying-textured bed forms. This indicates that the system could function in a wide variety of natural hydraulic environments with flow velocities up to 2 ft./sec. However, under dynamic conditions, the amount of response dispersion is increased to formidable levels. The increased dispersion, relative to static conditions, results from: 1) packing and density inconsistencies associated with sand migrating as natural bed forms, 2) differential settling and compaction during transport, and 3) different responses for erosional versus accretionary processes. The poor overall reproducibility resulting from these dynamic effects is the major factor limiting the utility of the gage systems as effective quantitative research instruments. Within the multiple-gage system, the relative effects of sediment texture on individual gages are essentially constant, although absolute pressure values for equivalent loads are variable, with each gage requiring its individual calibration curves.

Field testing of the single-gage system as a point sensor, and the multiple-gage system as an areal sensor, illustrate their potential as effective qualitative instruments in monitoring the long-period migration trends of beach sediments, with the only major extraneous variable being possible ground water effects. The short-period response of both systems is presently unreliable because of extraneous responses resulting from hydraulically-induced pressure differentials associated with breaking waves and surf. However, with future development, the short-period response may be substantially improved. Field tests further indicate that both systems, as presently constituted, are not sufficiently durable for extended field operations.

On the basis of this study, it is recommended that further development of the evaluated gage systems as quantitative instruments for measuring absolute sand-height values be terminated. This is based on the gages' formidable dispersion range resulting from its inability to differentiate responses resulting from actual sand-height variations, and those resulting from sand density variations induced by a wide spectrum of natural processes. It is also recommended that the gage systems be further developed as qualitative instruments for monitoring long-period migration trends of beach sediments. If further development is initiated, the systems' effectiveness can be greatly enchanced by incorporating a variable filter network to eliminate hydraulic noise. In addition, the field durability of the systems' components should be substantially increased, especially cables and connectors which are high-stress components, and are especially susceptible to failure. Effectiveness can be further enhanced by increasing the portability and operational time range of the systems' components. It is further concluded that the full qualitative potential of these gage systems can only be realized by operating as periodically-serviced remote recorders. Therefore, it is recommended that any future studies emphasize the feasibility of developing self-contained instrument packages designed for semi-permanent installation.

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